

**GEOLOGY AND GEOCHEMISTRY OF
THE NEGASH PLUTON AND THEIR
METALLOGENIC SIGNIFICANCE,
CENTRAL TIGRAI**

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By

Asfawossén Asrat
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By

Asfawossen Asrat
Department of Geology and Geophysics
Faculty of Science


Approved by the Examining Board

Prof. Angelo Peccerillo, Advisor

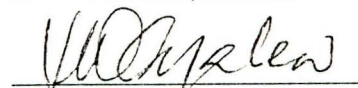
Dr. Tsegaye Abebe, External Examiner

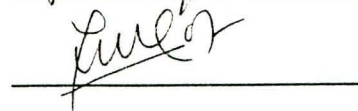
Dr. Teklewold Ayale, Examiner

Dr. Gezahegn Yirgu, Examiner



Tsegaye A
24/1/2017





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Geology and Geochemistry of the Negash Pluton and Their Metallogenic Significance, Central Tigrai

By

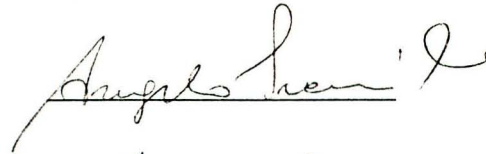
**Asfawossen Asrat
Faculty of Science**

Approved by :

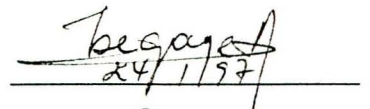
**Dr. Solomon Tadesse
Chairman**



**Prof. Angelo Peccerillo
Advisor**




**Dr. Tsegaye Abebe
External Examiner**



**Dr. Teklewold Ayalew
Examiner**



**Dr. Gezahegn Yirgu
Examiner**



CONTENTS

	<u>PAGE</u>
ABSTRACT	I
CONTENTS	II
LIST OF FIGURES	V
LIST OF PLATES	VII
LIST OF TABLES	VIII
ACKNOWLEDGMENT	IX
CHAPTER 1	
INTRODUCTION	1
1. 1. GENERAL INFORMATION	1
1. 2. PREVIOUS WORKS	3
1. 3. PRESENT STUDY	5
1. 3. 1. STATEMENT OF THE PROBLEM	5
1. 3. 2. OBJECTIVES AND SCOPE OF WORK	6
1. 4. PRECAMBRIAN ROCKS OF ETHIOPIA	8
1. 4. 1. GENERAL	8
1. 4. 2. THE PRECAMBRIAN BASEMENT STRATIGRAPHY	10
1. 4. 3. TECTONIC SETTING AND RELATED METALLOGENY	16
CHAPTER 2	
BASEMENT GEOLOGY AND STRATIGRAPHY OF TIGRAI	22
2. 1. GENERAL	22
2. 2. PRECAMBRIAN METAMORPHIC ROCKS	22
2. 3. PRECAMBRIAN INTRUSIVE ROCKS	27
CHAPTER 3	
GEOLOGY OF THE NEGASH AREA	30
3. 1. GENERAL	30
3. 2. THE METAVOLCANICS	31

3. 2. 1. FINE GRAINED METAVOLCANICS	33
3. 2. 2. METABRECCIAS	35
3. 2. 3. PORPHYROBLASTIC METAVOLCANICS	35
3. 2. 4. METASEDIMENTS	37
3. 3. THE NEGASH PLUTON	38
3. 3. 1. GRANODIORITES	39
3. 3. 2. TONALITES	41
3. 3. 3. DIORITES	42
3. 3. 4. QUARTZ PORPHYRY DIKES	46
3. 3. 5. APLITE DIKES	47
3. 3. 6. STRUCTURE OF THE NEGASH PLUTON	48
CHAPTER 4	
METAMORPHISM AND STRUCTURAL GEOLOGY	53
4. 1. METAMORPHISM	53
4. 1. 1. REGIONAL METAMORPHISM	53
4. 1. 2. CONTACT METAMORPHISM	55
4. 2. STRUCTURAL SETTING	57
4. 2. 1. FAULTS	58
CHAPTER 5	
GEOCHEMISTRY	62
5. 1. GENERAL	62
5. 2. GEOCHEMISTRY OF THE METAMORPHIC ROCKS	63
5. 2. 1. SAMPLING AND ANALYTICAL METHODS	63
5. 2. 2. RESULTS	70
5. 2. 3. INFERENCES ON THE NATURE OF THE PROTOLITHS	78
5. 2. 4. TECTONIC SETTING OF THE NEGASH METAVOLCANICS	81
CHAPTER 6	
GEOCHEMISTRY OF THE GRANITOIDS	84
6. 1. GENERAL	84
6. 2. COMPOSITION OF THE INTRUSIVE ROCKS	85

6. 3. TECTONIC SETTING OF THE NEGASH PLUTON	97
6. 4. PETROGENESIS	103
CHAPTER 7	
GEOCHEMICAL ANOMALIES AND ECONOMIC GEOLOGY	114
7. 1. GENERAL	114
7. 2. GEOCHEMICAL ANOMALIES	115
7. 2. 1. ZINC - LEAD ANOMALIES	115
7. 2. 2. GEOCHEMICAL ANOMALIES BASED ON TRACE ELEMENT ANALYSES	119
7. 3. CONCLUSIONS	124
CHAPTER 8	
CONCLUSIONS AND RECOMMENDATIONS	127
REFERENCES	129
APPENDIX A	
FIELD OBSERVATIONS IN SELECTED AREAS	134
A. 1. PEGMATITE VEINS AND RELATED MINERALIZATIONS	134
A.2. QUARTZ VEINS AND RELATED MINERALIZATIONS	134
A. 3. BARITE - FLUORITE MINERALIZATIONS	137
A. 4. HEMATITE - BARITE MINERALIZATION	145
A. 5. FELDSPAR DEPOSIT	146
APPENDIX B	
PETROGRAPHIC DESCRIPTION OF SOME SELECTED SAMPLES	147
B. 1. INTRUSIVE ROCKS	147
B. 2. METAMORPHIC ROCKS	152

LIST OF FIGURES

<u>FIGURE</u>	<u>Page</u>
Fig. 1. 1. Location map of the Negash area	2
Fig. 1. 2. Simplified geological map of Ethiopia (including Eritrea) (After Kazmin, 1975)	13
Fig. 1. 3. Tectonostratigraphic zones of the Ethiopian basement (including Eritrea) (After de Wt and Chewaka, 1980)	20
Fig. 3. 1. Stratigraphic outline of the Negash area	32
Fig. 3. 2. Stages of development of the Negash pluton	52
Fig. 5. 1. Sc - Variation diagrams for major and trace elements	72 - 74
Fig. 5. 2. REE patterns for the metamorphic rocks at different Sc - values	76
Fig. 5. 3. Incompatible element patterns for the metamorphic rocks at different Sc values	77
Fig. 5. 4. REE patterns for the different groups of metamorphic rocks	80
Fig. 5. 5. Discriminant diagrams for tectonic setting (After Wood et. al., 1979) (a) Th versus Hf diagram, (b) Th - Hf - Ta diagram	83
Fig. 6. 1. Classification diagrams. (a) After Le Bas et. al. (1986) (b) After Cox. et. al. (1979)	86
Fig. 6. 2. Silica versus alkali diagram	88
Fig. 6. 3. K ₂ O versus SiO ₂ classification diagram (After Peccerillo and Taylor, 1976) for the Negash granitoid rocks	88
Fig. 6. 4. Streckeisen classification diagram for intrusive rocks (After Streckeisen, 1975)	89
Fig. 6. 5. SiO ₂ variation diagrams for the major elements, Rocks from the Negash granitoid	91
Fig. 6. 6. SiO ₂ variation diagrams for trace elements, Rocks from the Negash granitoid	92 - 93

Fig. 6. 7. SiO ₂ variation diagrams for the REEs, Rocks from Negash granitoid	94
Fig. 6. 8. ACF diagram for rocks from the Negash granitoid	96
Fig. 6. 9. AFM diagram for rocks from the Negash granitoid	96
Fig. 6. 10. REE patterns at different silica content, for rocks from the Negash granitoid	98 - 99
Fig. 6. 11. SiO ₂ variation diagrams for Rb, Y, Yb, Ta and Tb, for rocks from Negash granitoid	101
Fig. 6. 12. Trace element discriminant diagrams (After Pearce et. al., 1984) For rocks from the Negash granitoid	102
Fig. 6. 13. Geochemical modeling on Th - SiO ₂ and Rb - SiO ₂ for the Negash granitoid	106
Fig. 6. 14. Geochemical modeling on Y - SiO ₂ and Zr - SiO ₂ for the Negash granitoid	107
Fig. 6. 15. Geochemical modeling on Ba - SiO ₂ and Sr - SiO ₂ for the Negash granitoid	109
Fig. 6. 16. Geochemical modeling on La - P ₂ O ₅ for the Negash granitoid	110
Fig. 6. 17. Geochemical modeling on Sc - SiO ₂ and V - Sc for the Negash granitoid	112
Fig. 7. 1. Geochemical sampling map for zinc in the Adi Desta area, Tigre (After Hagos, 1971)	117
Fig. 7. 2. Geochemical sampling map for lead in the Adi Desta area, Tigre (After Hagos, 1971)	118
Fig. A. 1. Detailed sketch map of a potassic alteration hosting quartz veins	138
Fig. A. 2. Detailed sketch map of a barite - fluorite vein	142

LIST OF PLATES

<u>PLATE</u>	<u>PAGE</u>
Plate 3. 1. A metabreccia, composed of big clasts which are elongated in one direction	36
Plate 3. 2. A close view of granodiorite. Big orthoclase grains can be easily recognised	40
Plate 3. 3. Granodiorite with microgranular mafic enclave (MME) (darker)	40
Plate 3. 4. Assimilation between mafic (darker) and felsic phases at the contact zone	44
Plate 3. 5. A microdiorite dike (dark) cutting the roof pendants	44
Plate 3. 6. Set of quartz and pegmatite veins (light) crossing tonalites near the contact to the diorites	45
Plate 3. 7. An aplite dike crossed by quartz veins	45
Plate 3. 8. Granodiorite affected by prevalent horizontal (hammock) jointing	49
Plate 3. 9. Closer view of horizontally jointed granodiorites	49
Plate 3. 10. Roof pendants (back ground) over the jointed granodiorites	50
Plate 4. 1. A roof - rock partially melted and compacted due to the effect of thermal metamorphism	56
Plate 4. 2. WNW - ESE trending fault (dipping south) South of the Negash pluton close to the contact	61
Plate 4. 3. The fault contact between Tsaliet group (left) and the Adigrat sandstone (right), which marks the "Wukro fault belt"	61
Plate A. 1. Quartz veins within potassic alteration. The quartz vein hosts hematite (dark)	139
Plate A. 2. Potassic alteration (flesh red) that shows well - developed feldspatization	139
Plate A. 3. Barite veinlets within potassic alteration and associated quartz veinlets	143

LIST OF TABLES

<u>TABLES</u>	<u>PAGE</u>
Table 1. 1. Precambrian units of Ethiopia (After Kazmin, 1972)	14
Table 1. 2. Correlation of some Precambrian units in East Africa and Arabia (After Kazmin, 1972)	15
Table 2.1. Schematic classification of the basement lithostratigraphic units in Central Tgrai (Modified After Alene et. al., 1995)	24
Table 5. 1.(a) Geochemical data for samples from the metamorphic rocks (Analysed by INAA)	64 - 65
Table 5. 1. (b) Geochemical data for samples from the Negash pluton (Analysed by INAA)	66 - 67
Table 5. 1. (c) Geochemical data for samples from the Negash pluton (For major elements, Analysed by XRF)	68
Table 5. 1. (d) Geochemical data for samples from the Negash pluton (For trace elements, Analysed by XRF)	69
Table 7. 1. Abundance of trace elements in various rocks (references) and the Negash metamorphic and intrusive rocks	121

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ABSTRACT

The Negash area is located in Central Tigray, Northern Ethiopia. The area consists of metamorphic rocks that are cut by some granitoid intrusions. The present investigation was directed to one of such intrusions, the Negash granitoid stock. Geological mapping at a scale of 1: 50 000, and geochemical studies led to the assessment of the petrology, geochemistry and tectonic setting of both the intrusion and the country rocks and the economic potential of the area.

The metamorphic rocks are mainly low - grade metavolcanic rocks with a wide compositional variation from tholeiitic to calc - alkaline mafic to felsic composition formed in an island arc environment. There are also minor intercalations of metasedimentary rocks. Hornblende - hornfels facies rocks are found in proximity to the intrusion.

The Negash granitoid body is undeformed, discordant, circular stock that consists of diorites, quartz diorites, tonalites, monzonites and granodiorites with minor aplitic, granitic and pegmatitic dikes. Its western boundary lies along a fault line (the Suluh Fault) that forms the Suluh River valley.

The intrusion is dominantly of mafic and intermediate composition rocks, even though the felsic rocks crop out extensively at the top most part of the intrusion.

Geochemical and petrological data suggest that the intrusive rocks were differentiated from a mafic magma by fractional crystallization and assimilation with fractional crystallization (AFC). Hornblende was the main fractionating mineral phase. This process resulted in relatively dry residual magma, as can be evidenced from the scarcity of pegmatites and related mineralization.

Preliminary geochemical survey of the Negash granitoid stock show no significant anomalies except for Zn and Sn. The country rocks show anomalies for several elements including Au, Zn, U, Sb, As and Ba. This indicates that the intrusive magma did not play an important role in generating mineralization in the area but it furnished the heat which triggered fluid circulation in the country rocks.

The geochemical anomalies for most of the elements are concentrated along the western boundary of the intrusion, the Suluh fault line. The fault presumably provided the ease through which the metasomatic fluids enriched the area with metals. Further geological and geochemical investigations should be directed to this zone.

CHAPTER 1

INTRODUCTION

1. 1. GENERAL INFORMATION

The area of the present study is located in Central Tigrai in the Wukro region west of a small village called Negash. This is located about 50 km north of Mekele, the capital of Tigrai, on the main road to Asmara. Hereafter, the study area is referred to as the “Negash Area” (Fig. 1. 1).

The Negash area is located at the northern most part of the “Mekele Sheet” and is bounded by latitudes $13^{\circ} 50' N$ to $14^{\circ} 00' N$ and longitudes $39^{\circ} 30' E$ to $39^{\circ} 40' E$.

The Negash Pluton, to which this study is primarily directed, is located roughly in the central part of the study area and access to this central part is difficult except on foot. The peripheral parts of the study area can be reached by four-wheel drive vehicles. Access by car to the intrusion is generally poor, except from the north.

The study area forms part of the Tigrai Plateau north of the “Mekele Outlier”. The altitude varies from 2500 m a. s. l. in the northeastern part to 2000 m a. s. l. in the southwestern part. The western part of the intrusion is cut by the Suluh River, the main river in the area, that flows southward. The area is dissected by perennial and intermittent streams all of which flow southwestward to the Suluh River, providing good cuts of the various lithologic units.

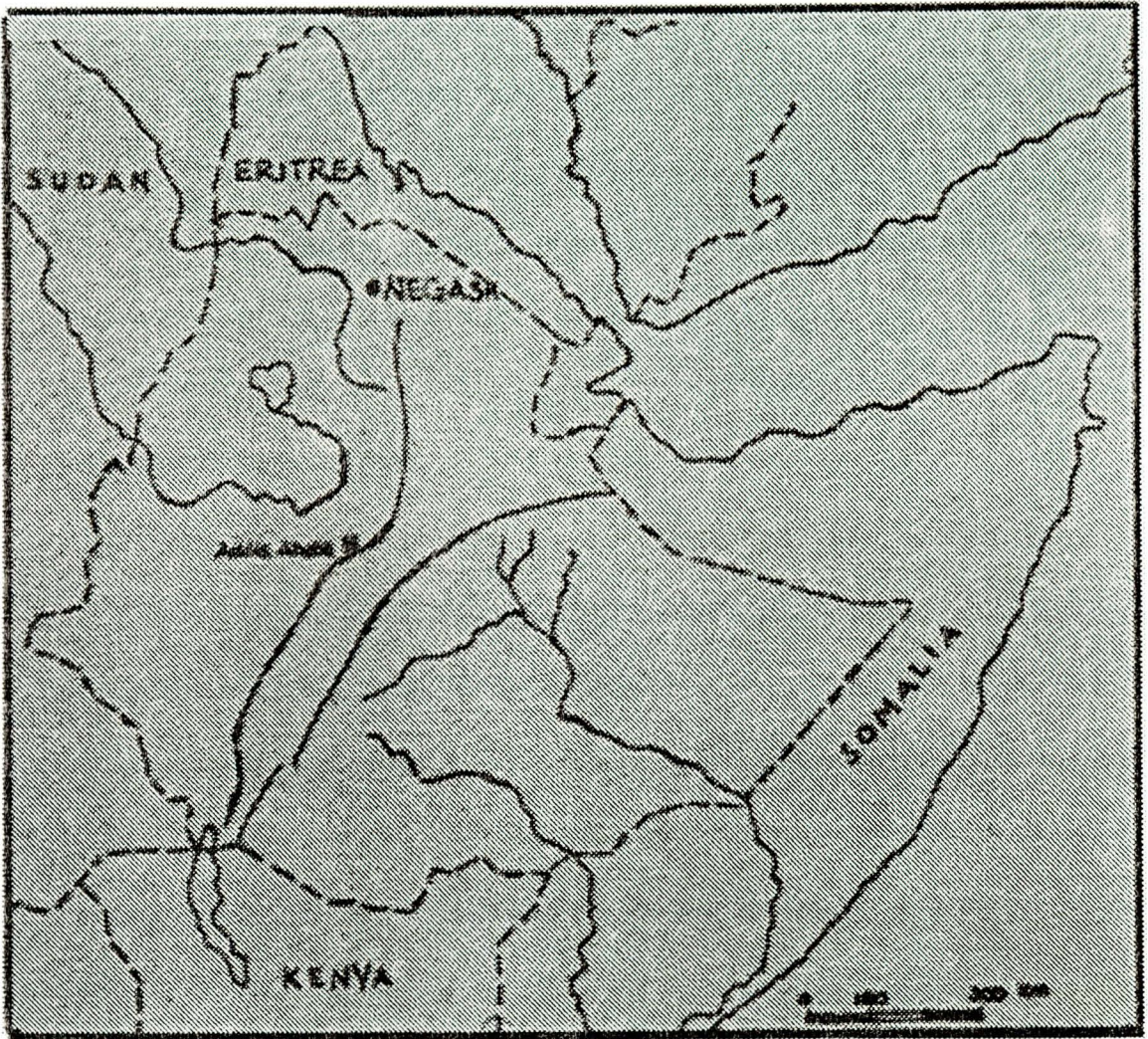


Fig. 1. 1. Location map of the Negash area.

Central Tigrai including the study area is characterized by a temperate climate with an average annual temperature and rainfall of 15 - 20 °C and 600 - 800 mm, respectively. The temperature ranges from minimum 5 °C to maximum 30 °C. The region is characterized by a dry season from September to May with minor weather changes and by a rainy season from June to August.

The area is poorly vegetated. The typical vegetation of the area, especially in the southwestern part, are short thorny bushes, shrubs, highland savanna with scattered tree patches of woodland where ever there are churches.

The area is densely populated. Except for some of the most rocky parts where no agricultural intrusion it is intensively cultivated.

1. 2. PREVIOUS WORKS

There have been various studies carried out on the geology of Tigrai. The first geological investigations started during the late nineteenth century during the British Expedition (Blanford, 1870). Later on, Merla and Minucci (1938) carried out a reconnaissance geological map of Tigrai at a scale of 1 : 400 000 with accompanying report in the "Memorie Geologica nel Tigrai", which has remained the standard reference work for subsequent geological research in the whole region.

The main conclusions of Merla and Minucci (1938), with some additional modifications, are embodied in the "Geologia dell'Africa Orientale" by Danielli (1941) who gave a detailed account of the basement complex and sedimentary sequences of the area.

in “ The Geology of Ethiopia” by Mohr (1965) who tentatively divided the Precambrian rocks of Ethiopia into an older and younger groups based on the degree of metamorphism.

Little further work was carried out until the late 1960's when the Ethiopian Institute of Geological Surveys produced a preliminary Geological map of Tigray province at a scale of 1 : 500 000 while prospecting for economic mineral deposits (Morton, 1975).

There have been some medium scale investigations in the region since the early 1970's. The most important studies in the immediate vicinity of the studied area include the works of Levitte (1970) who mapped the region systematically and subdivided the basement into four formations; the works of Beyth (1971) who gave a very detailed account on the lithologic description, classification, stratigraphy and mapping of the basement and sedimentary rocks in the area. Beyth (1971) also produced the geological map of the Mekele Sheet, including the study area, at a scale of 1 : 250 000 with accompanying explanatory notes.

Other relevant works include that of Garland (1980) on the “ Adigrat Sheet” area which lies immediately north of the Negash area and was geologically mapped at a scale of 1 : 250 000, who divided the basement rocks in the area into two groups and two formations.

Some other minor investigations in the area include the works of Assefa (1969) in the Werii area and Hamrla (1969) in the Samre area. Dow et. al (1971), Hagos (1971), Watters and W. Ruffael (1971) carried out stream sediment sampling in the Adi Desta which overlaps the present study area. Morton (1975) documented the geology of the Enticho area. Other preliminary minor investigations were conducted by the Ethiopian Institute of Geological Survey.

Since the mid seventies almost no geological investigations have been carried out in the area for nearly two decades when Kidane (1993) studied the tectonics of the Precambrian rocks of the Negash area which partly includes the area of the present study. The whole area has been recently studied by Tadesse (1994) who carried out mapping of the “Axum Sheet” area at a scale of 1 : 25 000 with an accompanying report that also explains the geotectonic evolution of the region in terms of plate tectonics. Temesgen (1995) mapped the area north west of Mekele using remote sensing techniques. Valera (1996) applied remote sensing techniques to map the Negash Granitoid and its surrounding. Other geological investigations are currently being undertaken in the area.

Regional works incorporating the Tigray region include those of Kazmin et al. (1978) and Berhe (1990) who tried to explain the geology of the region in terms of plate tectonics within the frame work of the Arabian Nubian Shield tectonic evolution.

1. 3. PRESENT STUDY

1. 3. 1. STATEMENT OF THE PROBLEM

The geology and economic geology of the metamorphic terrain of Tigray is not well known. Except for some regional and reconnaissance investigations by the Ethiopian Institute of Geological Survey (Jelenc, 1966), no detailed work has been carried out in the area previously. But currently the Tigray region has attracted the attention of prospectors and explorers. The geological mapping of the Mekele Sheet at a scale of 1 : 250 000 by the Ethiopian Institute of Geological Survey (Beyth, 1971) revealed some geochemical

anomalies for base metals such as zinc, lead and copper in the metavolcanics which are intruded by the Negash pluton. The authors had suggested that these occurrences may be related to the granitoid intrusion and recommended a further investigation.

The present study, therefore, investigates the Negash pluton as well as the country rocks.

1. 3. 2. OBJECTIVES AND SCOPE OF WORK

The main goals of the present work are:

1. To collect field data on the compositional and structural characteristics of the intrusion and of the country rocks.
2. To collect representative samples from both metamorphic and igneous rocks for petrographic and geochemical studies.
3. To determine major and trace element compositions of metamorphic and igneous rocks.
4. To identify reconnaissance level geochemical anomalies of rocks of the area to give a preliminary evaluation of the economic potential of the area
5. To explore the implications of the obtained geochemical and field data for the understanding of the nature of metamorphic rocks, the genesis and the evolution of the intrusive rocks and for the relationship between mineralizations and the intrusive and metamorphic events that affected the area. More specifically, discussion will be directed at understanding whether the granitoid intrusion is the source of the mineralizing fluids or simply provided the heat that triggered elemental mobilization, and ultimately at

investigating whether the intrusion has any economic potential, i. e., whether it is a metallogenic granitoid intrusion.

6. To provide suggestions for future development of prospecting and exploration of mineral deposits in the metamorphic terrain of Tigray.

In the course of the study, field work was conducted to map the intrusion and the enclosing rocks at a scale of 1 : 50 000. Aerial photographs at a scale of 1 : 50 000 and TM satellite images were used as base maps. Topographic and geological maps at a scale of 1 : 250 000 were also available and used for control checking.

Samples were collected from outcrops of the intrusion, the contact zones and the metamorphic rocks. Some stream sediments were also collected.

Petrographic description of selected samples is provided. The collected samples were prepared (crushing and grinding) for analysis in the Central laboratory of the Ethiopian Institute of Geological Survey. The powdered samples were then analyzed at the Dipartimento di Scienze della Terra, Università della Calabria, in Italy by X - Ray Fluorescence (XRF) method and partly in Canada by Instrumental Neutron Activation Analysis (INAA).

The data obtained from the field and the analytical results were treated statistically, critically discussed and interpreted. The prospects and geochemical anomalies were finally evaluated through their parameters. An Ms - Windows supported geochemical software called "IGPETWIN" was used in data processing and presentation.

1. 4. PRECAMBRIAN ROCKS OF ETHIOPIA

1. 4. 1. GENERAL

The Precambrian geology of Northeast Africa is not well known (Vail, 1976) and has remained a subject of intense discussion and debate up to the present time. The Precambrian basement of Ethiopia is part of this geological frame, and is of great interest because two major structures meet in Ethiopia : The Red Sea Belt (the Arabian - Nubian Arc) which is an Upper Proterozoic geosyncline, and the Mozambique Belt of East Africa in which older rocks suffered metamorphism and deformation in time roughly coincident with closure and folding in the Red Sea Belt (Kazmin, 1978).

Various studies have been carried out on the basement rocks of Ethiopia. Since the early seventies important data were gathered by the Ethiopian Institute of Geological Survey, The Omo river Project (1973, 1976), Gilboy (1970), Chater (1971), Beyth (1971), Mohr (1971), Kazmin (1971, 1972, 1973, 1975, 1978), Vail (1975), Garland (1980), deWit and Chewaka (1981), Warden et. al. (1982), Warden and Horkel (1984), Teklay (1986), Alene (1991), Kidane (1993), Tadesse (1994) and others. But the works of Kazmin (1971,1972,1973, 1975, 1978) have given the most outstanding contributions. A special mention is deserved by the geological maps of the country, including the Precambrian rocks, with accompanying explanatory notes compiled by Kazmin (1973) and by Merla et al (1979).

The basement rocks of Ethiopia comprise a wide variety of sedimentary, volcanic, and intrusive rocks metamorphosed to varying degrees from greenschist facies to amphibolite facies and locally granulite facies (Kazmin, 1971). They are exposed in the north

(parts of Tigray, Eritrea and Gondar), west and south west (parts of Gojjam, Wollega, Illubabor, Keffa and GamoGofa), South (parts of Sidamo and Bale), and in the east (parts of Hararghe). The rocks in the north are generally of lower grade metamorphism than those in the west and the south.

Apart from the metamorphic rocks, the basement complex is characterized by numerous granitic and ultrabasic intrusions to which most of the metallic mineralizations of the country including gold and the base metals are associated.

The absolute ages of the Precambrian so far available give ages between 976 and 415 Ma which apparently reflect only the younger (Upper Proterozoic, Rhiphaean) tectonic episode (Kazmin, 1971). While several post tectonic granitoids give late Precambrian or Lower Paleozoic absolute ages (e.g. Kazmin 1971, Vail 1976, Beyth 1971, Ayalew et. al., 1990).

Kazmin (1971) summarized the geologic history of the region. The Precambrian rocks were subjected to several orogenies, such as the Mozambique orogeny, since their formation. At the end of the Precambrian, uplift followed by a prolonged period of erosion occurred resulting in the removal of all sediments deposited above the basement except some shales and tillites of glacial origin in the North. During the Mesozoic, subsidence followed by a series of marine transgression and regression episodes occurred resulting in the sedimentary sequences of the country.

1. 4. 2. THE PRECAMBRIAN BASEMENT STRATIGRAPHY

The Precambrian rocks of Ethiopia are grouped into three main divisions by Kazmin (1971, 1975) and other subsequent researchers as :

The Lower Complex	<i>Oldest</i>
The Middle Complex	
The Upper Complex	<i>Youngest</i>

These three complexes are characterized by different lithology, nature and degree of metamorphism, and structural styles of deformation. These stratigraphic units in different parts of the Ethiopian basement are correlated in Table 1.1. and with the basement rocks of East Africa and Arabia in Table 1.2. (After Kazmin, 1972).

The Lower Complex

The Lower Complex comprises various gneisses and migmatites, mainly granitic, and represents the oldest cratonic basement rocks in the country. Lithologically, the rocks mainly consist of biotite- and amphibole-gneisses with minor quartz-feldspathic granitic gneisses, calc-silicate rocks and amphibolites, which are metamorphosed up to amphibolite facies, locally to granulite facies (pyroxene and amphibolite - pyroxene gneisses). The major structures are broad, gently dipping synforms and antiforms.

The lower Complex is believed to be a direct north ward continuation of the basement system of Kenya, of northeastern Uganda and of south eastern Sudan (e. g. Vail

1976, Kazmin 1978).The rocks of the Lower Complex are extensively cropping out in Southern and Western Ethiopia and, partially, in the east (Fig. 1. 2.).

The Middle Complex

The Middle Complex, which have been identified only in Sidamo and Hararghe, is represented by psammitic and pelitic metasediments with metamorphic sandstones and quartzites which formed an ancient cover over the granite - gneissic complex. Primary sedimentary features such as cross - bedding are sometimes well preserved and the metamorphic grade has never exceeded amphibolite facies.

The Middle Complex is considered to be the accumulation of clastic sediments as a platform cover in depressions in the lower basement. Its distribution is controlled by large Precambrian faults, reflecting the early stages of rifting which later led to the formation of the Upper Proterozoic fold belt (Kazmin, 1978).

The Upper Complex

The Upper Complex is a very thick, younger geosynclinal succession, composed of low grade (very slight metamorphic alteration to greenschist facies, locally low amphibolite facies) but tightly folded rocks including ophiolitic intrusives (ultrabasics, gabbros, amphibolites), metavolcanics and metasediments (graphitic schists and phyllites), clastic and carbonate metasediments with the primary sedimentary structures commonly preserved (Fiori et. al., 1988).

The rocks of the Upper Complex are outcropping in Sidamo (Adola Group), in Wollega, and in the North (Tigrai) where they form most of the Precambrian basement (for a detailed discussion of the Upper Complex in the North, refer to Section 2.1.).

INTRUSIVE ROCKS

Apart from the metamorphic assemblages, the Precambrian basement is commonly intruded by syntectonic and several generations of post-tectonic granitoid bodies and associated vein rocks (i.e. pegmatites and aplites, quartz veins, and quartz porphyry dikes). Intrusive rocks have variable composition, texture, and age (dated 690 - 450 Ma, Ayalew et al., 1990).

Ultrabasic intrusives belonging to the ophiolite sequences are also common in the Upper Complex. The serpentinites and talc schists of Kenticha, (Sidamo), metagabbros, amphibolites and talc - tremolite - actinolite schists of Adola, Sidamo (Fiori et al, 1988) and Moyale (Alene, 1991), dunites with minor pyroxenites and peridotites of Birbir Basin, Wollega (e. g. Augustithis 1965, Getahun 1985), and the ultramafic "melange" in north western Tigrai (Tadesse, 1994) are the most conspicuous mafic and ultramafic intrusives in the basement.

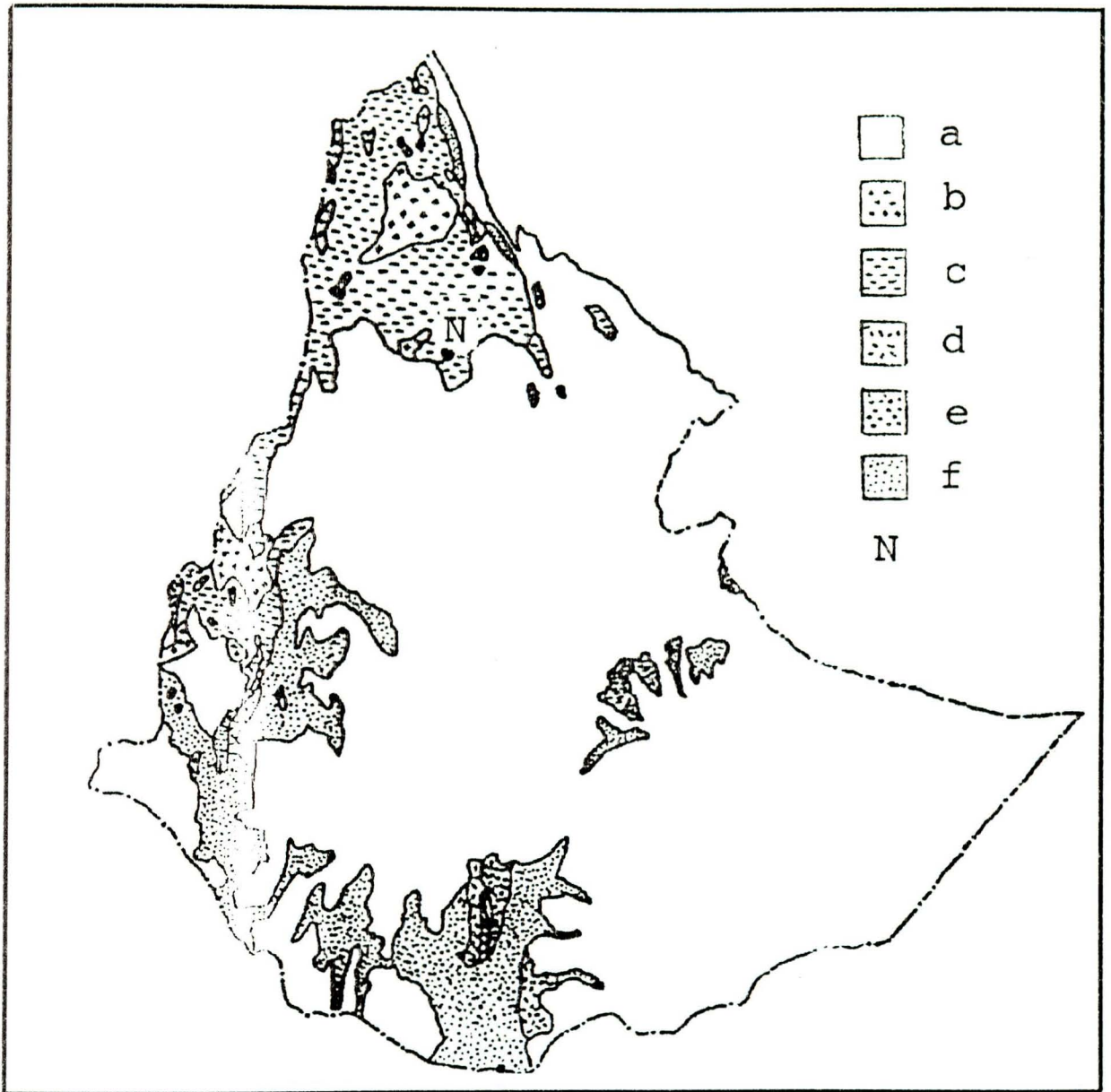


Fig. 1. 2. Simplified geological map of Ethiopia (Including Eritrea) (After Kazmin, 1975) a) Phanerozoic cover, b) Precambrian granitoids, c) & d) Upper Complex e) Middle Complex, f) Lower Complex, N) Negash pluton

Table 1. 1 Precambrian Units of Ethiopia (After Kazmin, 1972)

AGE	SOUTHERN ETHIOPIA	WESTERN ETHIOPIA	NORTHERN ETHIOPIA	HARRAR AND AISHA	COMPLEX	
EOCAMBRIAN			MATHEOS FM.		UPPER	
UPPER PROTEROZOIC			SHERARO FM.			
			DIDIKAMA FM.			
			TAMBIEN GR.			AMOTA FM.
						MAIKENETAL FM.
						AREQUA FM.
KAJIMITI BEDS AND MORMORA GROUP	BIRBIR GROUP	TSALIET GROUP	SOKA AND BOJE SERIES			
ADOLA GROUP	GREENSTONES & AMPHIBOLITES					
L- M PROT.	WADERA GROUP			MIDDLE		
ARCHAEAN	BURJI GNEISS	GNEISSES UNDIFFERENTIATED	GNEISSES UNDIFFERENTIATED	MICA SCHIST	LOWER	
	ARERO GR.			YAVELLO GNEISS		
				AWATA GNEISS		
				ALGHE GNEISS		
KONSO GNEISS	GRANULITES					

Table 1.2 Correlation of Some Precambrian Units in East Africa and Arabia (After Kazmin, 1972)

AGE		SAUDI ARABIA	EGYPT	SUDAN	ETHIOPIA	SOMALIA	KENYA	TANZANIA
INFRACAMBRIAN OR EOCAMBRIAN		Fatima, Abla Fms.	Hammamat Series	Awat Series	Sheraro Fm. Matheos Fm.			
UPPER PROTE ROZOIC	UPPER PART	Murrdama Fm. Halaban Fm.	Schist - Mudstone - Greywacke Series Dokhan Series	Upper Part Nafirdeib Series Lower Part	Tambien Gr. Tsaliel Gr.	Inda - Ad Series		
	LOWER PART	Beish, Lit Complexes	Shadli Series Barramia Rocks	Primitive System	Adola Gr.	Green Rock Series	Green Rock Complexes (Wester N Kenya) Embu and Ablun Series (Eastern Kenya)	Ukinga, Konse, Ndembera Series
MIDDLE - LOWER PROTEROZOIC		?	?		Wadera Gr.	?	Turoka Series	Limestone Graphite Series
ARCHAEAN		Ancient Gneiss	Orthogneisses of Basement, Mitiq Series		Burji Gneiss Arrero Gr. Konso Gneiss	Gneisses of the Basement System	Basemnet System	Usagaran System

1. 4. 3. TECTONIC SETTING AND RELATED METALLOGENY

Detailed studies of the petrology and stratigraphy of the Ethiopian Precambrian basement, have allowed Kazmin et al. (1978) to suggest the following evolutionary history:

The ancient cratonic basement (Lower Complex) was formed during the Archaean. The high grade and tightly folded, granulite facies metamorphic rocks of the Mozambique gneisses were later subjected to refolding and amphibolite facies metamorphism. During the Lower to Middle Proterozoic, platform type psammitic and pelitic sediments of the Middle Complex were accumulated in depressions of the stable craton. The ancient basement rifted in zones corresponding to the present-day red Sea area. Zones of oceanic crust opened, which pinched out to the south and only continued as continental rifts with attenuated crust along the whole or part of the Mozambique belt. About 1000 - 900 Ma ago, continental convergence occurred in the zone of the present Red Sea, accompanied by subduction of oceanic crust resulting in arc - type volcanism. This was followed by a period of collision and folding about 1000 - 800 or 700 Ma ago. In the narrow southern parts, the continental convergent zone was characterized by the formation of ophiolitic sutures. During the Late Proterozoic or Lower Palaeozoic post - tectonic granitoid intrusions affect the Precambrian basement.

The subduction model of Kazmin et al. (1978) fit to the unified models for north east Africa (e. g. de Wit and Chewaka 1981, Gass 1982, Vail 1985, Kroner 1985, Shackelton 1986).

de Wit and Chewaka (1981) tried to clarify the concepts of Kazmin et al. (1978) and classified the Ethiopian basement into five major tectonostratigraphic zones, and suggested a

possible association between these zones and the various metallogenic occurrences. These zones (Fig. 1. 3.) are :

Zone 1: Calc - Alkaline Volcanic Plutonic Belt

This belt is a palaeo calc-alkaline arc, built on pre - existing continental crust, that can be traced for some 1200 km along western Ethiopia. In Tigrai and Eritrea it is represented by the Tsaliyet Group. The present study area belongs to this belt. This belt comprises a volcano - sedimentary succession of metavolcanics of andesitic and dacitic composition, various volcanoclastic rocks, tuffs, rhyolitic agglomerates, phyllites, schists, quartzites and arkoses with intercalations of cherts and marbles. The all belt is intruded by numerous granitoid bodies. The southern part of the belt is more strongly metamorphosed and deformed than the northern part.

There are both Kuroko type polymetallic stratiform deposits and copper porphyry type deposits associated with this belt, indicating a Japan - type ensialic volcanic arc. Gold mineralization is also associated with this belt. Because of the higher deformation in the southern parts, tectonically induced mineralization might be of greater importance in the area than the northern extremities of the belt.

Zone 2: Western Ophiolite Suture Zone

This belt runs through south west Ethiopia for some 500 km, from the Kenyan border to the Blue Nile and possibly further north. They are represented by the ophiolite complexes

of Berhe (1990) and the ultramafic belts of Tadesse (1994) in the northern parts (Tigray and Eritrea). This belt consists of metagabbros and serpentinized ultramafic complex unconformably overlain by a sequence of probable deep water metasediments and ultramafic metavolcano - clastics and metasilicic volcanics. This belt cuts the calc - alkaline belt and represents remnants of inter - arc or back arc basin, probably comparable to the present Japan Sea.

Ultramafic associated mineralizations of Pt, Ni, Co, Cr, asbestos and possibly Cyprus or Besshi type copper - iron sulphide deposits are expected in this belt as indicated by de Wit and Berg (1977), Augustithis (1965) and others.

Zone 3: Central High Grade Area

This belt occupies the area north east of Lake Rudolf and constitutes rocks of high metamorphic grade (lower part of the Lower Complex), including a series of mafic gneisses and granulites, layered biotite and hornblende gneisses, quartzo - feldspathic gneisses, migmatites and paragneisses. This zone is a high grade metamorphic belt which could be the result of collision and subsequent subduction of oceanic crust below volcanic arcs. It may represent the area between an arc and a trench.

There are some occurrences of chalcopyrite, pyrrhotite and pyrite disseminations in the ultramafic bodies of this belt and locally some molybdenite occurrences in veins are recognized.

Zone 4: The Eastern Metamorphic Belt

This belt, which is represented by the Adola metamorphic belt in the south, is the area where all the three stratigraphic units (the Lower, Middle and Upper Complex) are well exposed. The tectonic setting of this zone resembles that of a passive rifted margin such as the present Indian Ocean continental margin, where rifting of the continental crust (Lower Complex) was accompanied by basaltic volcanicity and clastic sedimentation (Middle Complex). It may represent intercontinental to intracontinental rifting followed by sea floor spreading which gave rise to the formation of oceanic crust as represented by the ophiolites.

The ophiolite rocks in this belt are characterized by similar mineralizations as that of Zone 2 (Kazmin, 1981). The Adola area is affected by gold mineralization associated with hydrothermal quartz veins with sulphides, lense - like quartz intrusions in massive amphibolites, in quartzites and meta - conglomerates (Fiori et al., 1988).

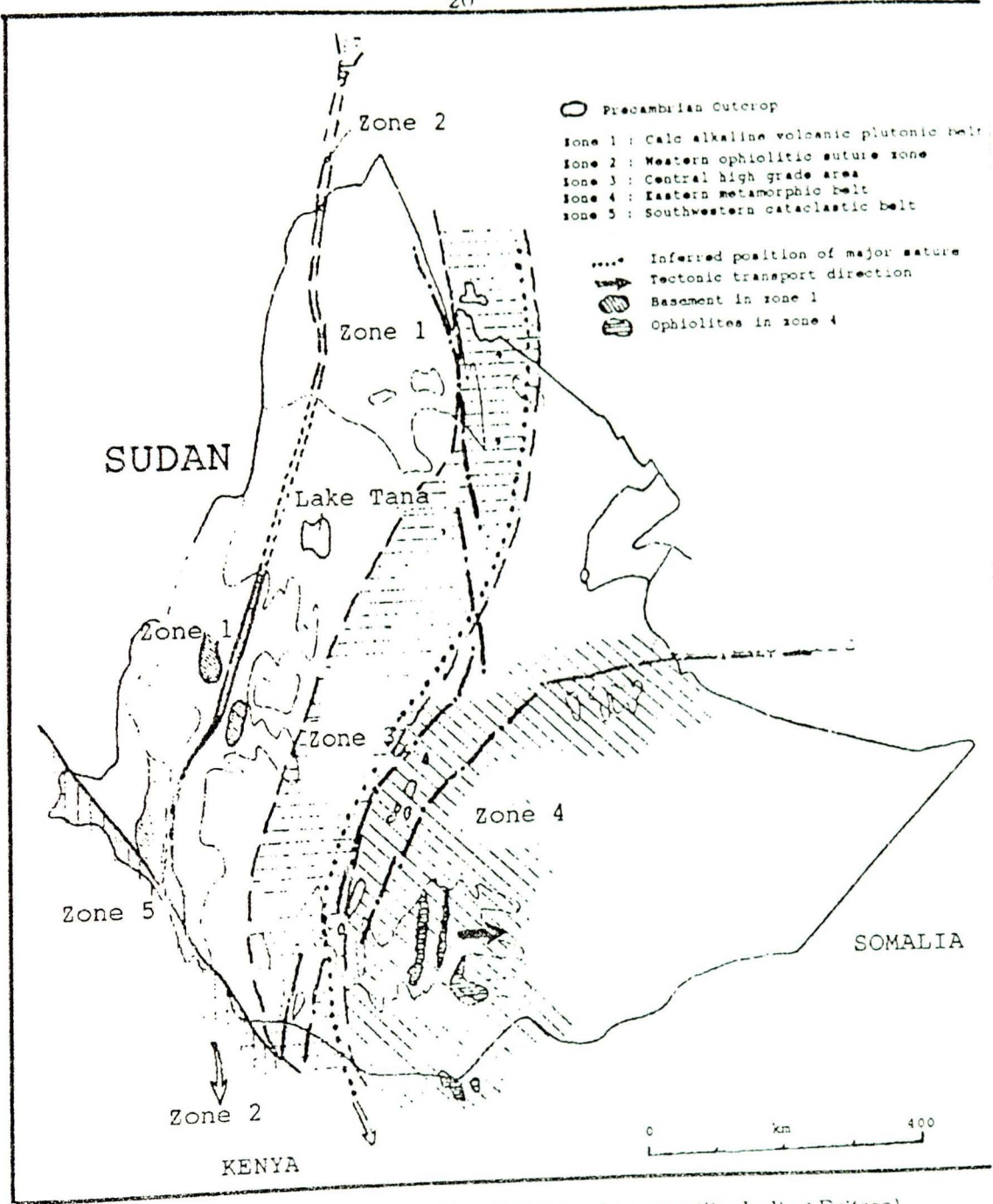


Fig. 1. 3. Tectonostratigraphic zones of The Ethiopian basement(including Eritrea)
 (After de Wit and Chewaka, 1980)

Zone 5: South Western Cataclastic Belt

This belt is a mega - shear along the Sudanese border and can be traced for long distance north - west striking in Sudan. This belt may represents continent - continent collision of African craton with an undefined eastern continent. Several of the recognized ring complexes of the Ethiopian Precambrian and many of the post - tectonic granitoids in southern, western and northern Ethiopia, including the granitoid intrusion of the present study could belong to this belt.

Tin and Tungsten mineralization, with minor Nb, Tl, Be, Li, F, U, and Th are associated with the granitoid intrusions and Ti with the gabbroic intrusives.

de Wit and Chewaka (1981) stressed the need for much greater effort to investigate these ring complexes to ascertain their age and likelihood of associated mineralization of these highly incompatible elements and other possible mineralizations. The purpose of the present study is partly to investigate for such possible mineralizations in one of the recognized granitoids, in Tigrai.

CHAPTER 2

BASEMENT GEOLOGY AND STRATIGRAPHY OF TIGRAI

2. 1. GENERAL

The Tigrai region is characterized by rock assemblages which cover a wide geologic time. The Southern part is represented by Cenozoic volcanic rocks, the central part is represented by the Palaeozoic and Mesozoic sedimentary successions of the "Mekele Outlier", whereas the Northern and Northwestern parts which extended to Eritrea are dominantly characterized by steeply dipping and extensively folded, rather low grade metamorphic rocks of the Upper Complex, intruded by various intrusions. The study area is constituted by one of these intrusions surrounded by metamorphic rocks of the Precambrian Upper Complex which are, in turn, unconformably related to the sedimentary rocks of "Mekele Outlier" to the South.

2. 2. PRECAMBRIAN METAMORPHIC ROCKS

Except for some limited outcrops of the Lower Complex in areas North of Adigrat (Garland, 1980), the Precambrian rocks of Tigrai are represented by a series of thick, inhomogeneous units of volcanic and sedimentary rocks of the Upper Complex (Kazmin, 1971, 1972). There is no any indication of the Middle Complex rocks in the region.

Various researchers tried to give a stratigraphic outline of the Precambrian rocks in the area but they never come up with a single Precambrian stratigraphy. The work of the

major researchers is summarized by Alene et. al (1994) and is presented here with some modifications in Table 2.1. Although the various researchers differ in their use of the stratigraphic nomenclature, the rock units are described similarly by all.

Tsaliet Group

Named after the Type Area in Tsaliet river in central Tigray (Beyth, 1971), this unit is composed of a heterogeneous volcanic rocks such as breccias, agglomerates, bedded tuffs and lavas, all interbedded with marine clastics, rare limestones, tuffaceous slates, redeposited ash, and greywacke composed partly of volcanic fragments, exhibiting considerable lateral variation. The Tsaliet Group forms an extensive outcrop with a thickness reaching up to 2,500 m in some sections (Garland, 1980) and shows a general regional trend of $N20^{\circ} E/55^{\circ} NW$ to $N30^{\circ} E/55^{\circ} NW$ (Levitte, 1970). These rocks which constitute the country rocks of the present study area are correlated with the Birbir Group of Western Ethiopia, Mormora Group and Kadjimiti beds of Southern Ethiopia, Soka and Boje Series of Hararghe and Aisha, the Halaban Formation of South Arabia, the Dokhan Series of Egypt, and Lower part of the Upper Proterozoic of Sudan (Kazmin, 1972). The Tsaliet Group belongs to the Calc - Alkaline Volcanic Plutonic Belt of deWit and Chewaka (1980).

Tambien Group

This unit conformably overlies the Tsaliet Group with a gradational contact marked by thin beds of limestone (Garland, 1980). According to Beyth and Dow (1979), this group comprises four members, from the oldest to the youngest : Werii Slate, Assem Limestone,

Table 2.1. Schematic Classification of the Basement Lithostratigraphic Units in Central Tigray (Modified After Alene et. al., 1995)

AGE	Based on Beyth (1971) (Mekelle Sheet)	Based on Garland (1980) (Adigrat Sheet)	Based on Kazmin (1972)	Based on Tarekegn (1993) (Axum Sheet)
Lower Palaeozoic - Late Pre-cambrian	Mereb Granite Forstaga Diorite	Post - Tectonic Intrusions (Granites, Granodiorites, Diorites) Syntectonic Granitoids (Foliated Granites)	Post - tectonic Granitoids	Post - tectonic Granitoids Late tectonic Granitoids Syntectonic Granitoids
Upper Proterozoic (Pre - cambrian Upper Complex) (Riphaean)	T a m b i e n G r o u p W e r i S l a t e A s s e m L i m e s t o n e T s e d i a S l a t e M a i K e n e t a l L i m e s t o n e U n d i f f e r e n t i a t e d B a s e m e n t U n i t s	Upper Complex Not Differentiated	(Gabbro)	The Sheraro Block (The Sheraro Group)
		T a m b i e n G r o u p W e r i S l a t e A s s e m L i m e s t o n e T s e d i a S l a t e M a i K e n e t a l L i m e s t o n e U n d i f f e r e n t i a t e d B a s e m e n t U n i t s	Matheos Formation Didikama Formation Arequa Formation (Undifferentiated)	
		G r o u p W e r i S l a t e A s s e m L i m e s t o n e T s e d i a S l a t e M a i K e n e t a l L i m e s t o n e U n d i f f e r e n t i a t e d B a s e m e n t U n i t s	A r e q u a F M Ultrabasics Tsaliet & Tambien Groups Undifferentiated Tambien Group	
	Tsaliet Metavolcanics	Tsaliet Group	Tsaliet Group	The Adwa - Adihaftom Block The Chila Block The Adi Nebriid Block The Adihageray Mafalso Block

Tsedia Slate and Maikenetal Limestone. The former three have been grouped into one as the Arequa Formation by Hailu (1971) (in Garland, 1980).

Werii slate

The Werii slate consists of black, graphitic or variegated slates or phyllites, originally well laminated mud stones, with thin intercalations of limestones, calcareous sandstone, greywacke and occasional intraformational conglomerates (Garland, 1980). Towards the top it is cut by quartz - biotite - diorite dikes and quartz veins (Beyth, 1971).

Assem Limestone

The Assem Limestone which conformably overlies the Werii Slate is a well bedded, finely laminated black limestone with some calcareous shale, dolomite and silicified lenses in places (Garland, 1980). It is interbedded with slate and its boundary with the Werii Slate is arbitrarily defined where the limestone beds become dominant while the upper contact with the Tsedia Slate is sharp (Beyth, 1971). The maximum thickness of the whole unit is not more than 300 m (Garland, 1980) and dips steeply (Levitte, 1970).

Tsedia Slate

The Tsedia Slate at the base is composed of purple slates but it resembles the Werii Slate in the upper part of the section, being partly graphitic, well - laminated and interbedded with thin calcareous sandstones. The maximum thickness is about 500 m. Often it is cut by



aplitic dikes and is conformably overlain by the Mai Kenetal Limestone, in which the boundary is arbitrarily placed where the limestone beds become dominant (Kidane, 1993).

Mai Kenetal Limestone

The Mai Kenetal Limestone is recognized and described by Beyth (1971). It is composed entirely of fine crystalline black limestones containing detrital algal fragments, ooliths and rare plagioclase crystals.

Didikama Formation

The Didikama Formation unconformably overlies the Tambien Group. It was named by Hailu (1971) (in Garland, 1980) after the outcrop at Didikama in the Sheraro area. It consists of yellowish, medium grained dolomite interbedded with gray, black or coloured slates. The dolomite contains a good deal of sand or mud, in places grading into talc schist or calcareous shale, while most of the clastic units are either sandy greywacke (green slate) or cherty mudstone (phyllite) (Garland, 1980).

Matheos Formation

This formation, which according to Garland (1980) is known only in the Negash Syncline, is thought to be the youngest Precambrian formation in Ethiopia. This formation has less than 30 m maximum thickness and is folded into a gentle syncline. It overlies the

Didikama Formation, with angular unconformity. It consists of gray to black colored, well laminated and undisturbed limestone, partly detrital, veined with calcite (Garland, 1980). The limestone occurs as micritic, oolitic and fragmental varieties (Beyth, 1971).

Undifferentiated Upper Complex

This complex is composed of both metavolcanics and metasediments which can possibly belong to the Tambien Group or the Tsaliet Metavolcanics. This unit outcrops in Northern Ethiopia along the faces of escarpments in the eastern part of the Mekele Area (Levitte, 1971) and in Eritrea (Garland, 1980).

2. 3. PRECAMBRIAN INTRUSIVE ROCKS

The Tigrai region and Eritrea are characterized by a considerable number of basic and acidic intrusive bodies cutting the metamorphic rocks, among which the acidic intrusives are dominant. All Beyth (1971), Kazmin (1972) and Garland (1980) identified two types of granitoid intrusions : the Syntectonic and post - tectonic granitoids while Tadesse (1994) identified three types of granitoid intrusions in the region, the third being the late - tectonic granitoids in addition to the two former types.

The Syntectonic Granitoids

These granitoids are represented by rather weathered, medium grained epidotized, foliated granites elongated along the regional strike. There are also some foliated granodiorites of limited exposure cutting the metavolcanics in some places (Garland, 1980).

The Post - Tectonic Granitoids

The Post - tectonic granitoids are represented by granites, granodiorites, tonalites, quartz diorites and diorites which are associated in place. These, in turn, are cut by many late stage aplite and quartz porphyry dikes. There is no clear contact between the granodiorites and the tonalites but there is a gradational change in the amount of the mafic minerals.

The granitic and granodioritic stocks in the region are named as the "**Mereb Granite**" after the exposure in the Mereb river, and the diorites and quartz diorite masses as the "**Forstaga Diorite**" after the Forstaga village in the North eastern part of the Mekele Sheet, by Beyth (1971).

The post - tectonic granites are generally coarse grained alkali potassic granites although porphyritic microgranites are not uncommon. They are commonly composed of quartz, microcline perthite, zoned plagioclase, biotite and minor green pleochroic hornblende, with sphene and apatite as accessory minerals. Chemically, the major constituents are found out to be $\text{SiO}_2 = 63.6 - 68.2 \%$, $\text{Al}_2\text{O}_3 = 14.0 - 18.4 \%$, $\text{Na}_2\text{O} = 5.9 - 7.1 \%$ and $\text{K}_2\text{O} = 2.7 - 2.9 \%$ (Garland, 1980). However, the silica contents are too low for typical granites. Beyth (1971) recognized many other varieties of granitoid intrusions. Pink granites are exposed to the west and east of the granitoid stock of the present study area.

There are also some granite bodies in the northernmost part of Tigray like the Assimba Peak, and a number of rounded bodies in the northern part of the region (Garland, 1980). The granites are frequently and extensively cut by aplite, quartz porphyry dikes and pegmatites.

The granodiorites are commonly associated with granites, and are composed of quartz, plagioclase, microcline \pm biotite, secondary muscovite and chlorite.

The diorites in the region are medium grained, often containing quartz but in places are quartz-free. The Forstaga diorite is a quartz - amphibole diorite containing biotite and pyroxene, epidote and chlorite (Beyth, 1971). In places it grades into granodiorite/ Tonalite. Chemically, the major constituents are $\text{SiO}_2 = 53.5 - 58.6 \%$, $\text{Al}_2\text{O}_3 = 12.5 - 16.2 \%$, $\text{CaO} = 6.0 - 6.3 \%$ and $\text{K}_2\text{O} = 1.2 - 2.7 \%$ (Beyth, 1971). Beyth (1971) also proposed that the diorite had been intruded before the granite and is foliated in parts of the Mekele area.

The ages of the post - tectonic granitoids in this region are put in the Upper Proterozoic - Lower Palaeozoic. There have been some K/Ar absolute age determinations of the post - tectonic granitoid rocks. Three post - tectonic granodiorite specimens from Adi Aro river in the Adigrat Sheet area gave 582 ± 21 Ma, 570 ± 31 Ma and 582 ± 22 Ma. At the same time two pink granite specimens from Hauzien (immediately West of the present study area) gave K/Ar ages of 583 ± 16 Ma and 621 ± 27 Ma. Granites from the Mereb river gave 690 ± 4 Ma and 670 ± 5 Ma (Garland, 1980).

$^{40}\text{Ar}/\text{Ar}^{39}$ dating carried out on K-feldspars and micas separated from a granodiorite from the Negash pluton has given an age of 660 ± 10 for muscovite, 676 - 589 Ma for biotite and 593 - 555 Ma for K - feldspars. Since there is evidence of Argon loss from feldspars, the ages of micas can be considered as emplacement age of the pluton (Arnaud et al., 1996).

CHAPTER 3

GEOLOGY OF THE NEGASH AREA

3. 1. GENERAL

The studied area has been mapped on a 1 : 50,000 scale using similar scale aerial photographs and TM Satellite Imageries as base maps. The lack of a 1 : 50,000 scale topographic base map has been one of the constraints during the course of mapping.

The central part of the mapped area is represented by the metavolcanics of the Tsaliyet Group intruded by the granitoid stock. The metavolcanics show a considerable lateral variation in lithology and are mapped as a single unit, but there are different lithologies which are described separately. The metavolcanics are intercalated with some thin beds of metasediments and are metamorphosed to greenschist facies metamorphism. Higher grade of metamorphism is observed at the contact with the granitoid stock.

The granitoid stock shows radially arranged lithological units of granodiorite, tonalite, diorite and quartz diorite. Granodiorite also crop out towards the centre of the intrusion. The stock is cut by a series of aplitic and quartz porphyry dikes and are sub - parallel to each other and to the regional foliation direction of the metavolcanics. Numerous quartz veins and pegmatites are also observed within the stock and in the metavolcanics near the contact. In addition, there are patches of roof rocks and cap rocks at various localities within the intrusion.

To the West and the North, the metavolcanics show a clear and sharp contact with the overlying Palaeozoic sediments of the Edaga Arbi Glacials and the Enticho Sandstone. To

the South, the Mesozoic Adigrat Sandstone of the "Mekele Outlier" unconformably overlies the metavolcanics. To the East the metavolcanics show a sharp contact with Tambien Group rocks of the Negash Synclorium.

Although field investigation, description and sampling have been concentrated in and around the granitoid stock, a general stratigraphic outline of the studied area was compiled and is given in Fig. 3. 1. No attempt has been made to describe and sample the other rock units because first, the sedimentary rocks are younger than the intrusion and they do not have any influence on the genesis and possibly associated mineralizations of the intrusion and second, the granitoid stock is totally surrounded by the metavolcanics and the Tambien Group rocks belong to a different structural block.

3. 2. THE METAVOLCANICS

The larger part of the study area is covered by strongly foliated, steeply dipping and folded metavolcanic rocks that form extensive plains and flat tops. The mean foliation direction of the unit is N 30° E. Other metamorphic and sedimentary rocks rest unconformably on the metavolcanic rocks.

The metavolcanic rocks with the interstratified minor metasediments are correlated with the Tsaliet Group of Beyth (1971). Beyth (1971) and Garland (1980) ascribed the origin of the Tsaliet Group to volcanic rocks formed under water, interpreted based on the presence of primary sedimentary structures like ripple marks and slump structures, which are also observed in the Negash area.

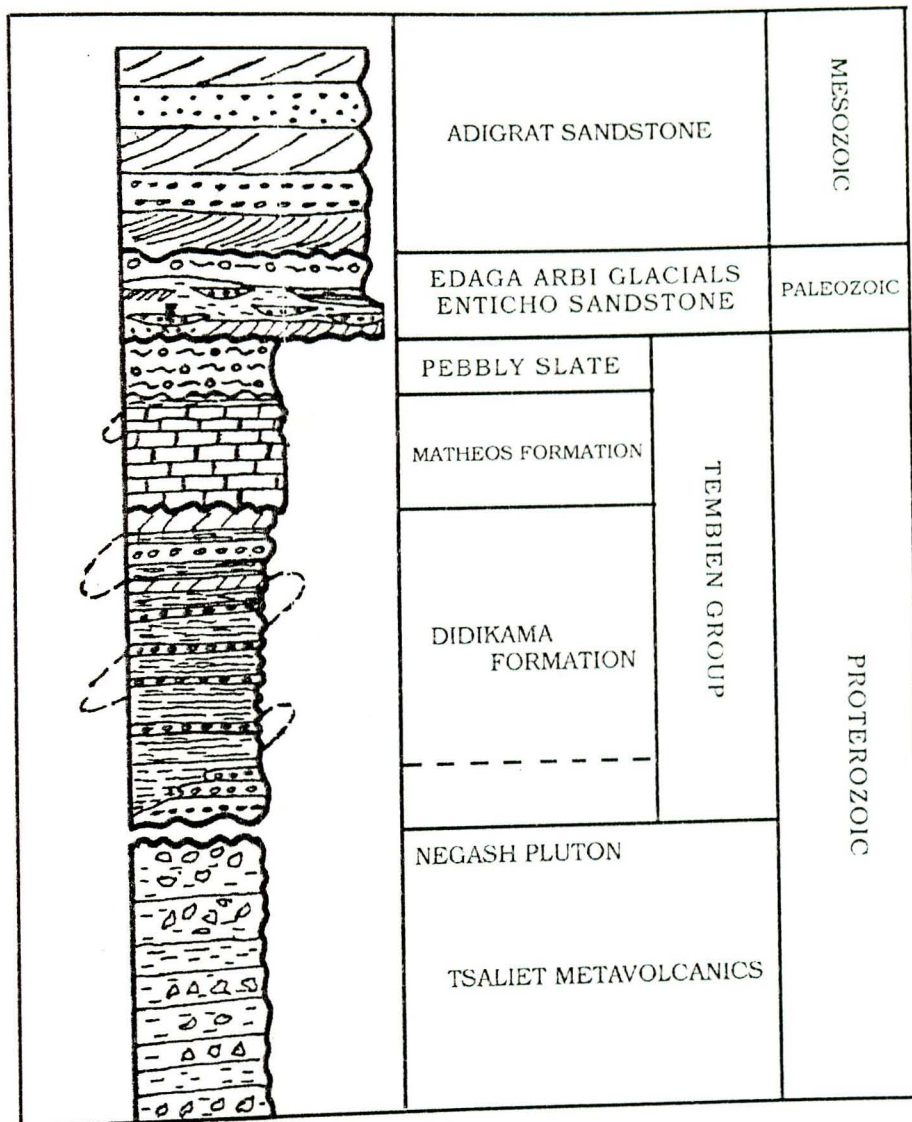


Fig. 3. 1. Stratigraphic outline of the Negash Area

Away from the contact with the intrusive body, the rocks are of greenschist facies and are generally represented by fine grained to porphyroblastic metavolcanic rocks intercalated with thin beds of metasediments. Near the western contact, breccias are commonly represented while the remaining contact aureole is represented by the fine grained to porphyroblastic metavolcanics. Some spotted schist containing visible crystals of garnet, biotite and hornblende do also occur. Contact aureoles of the hornblende - hornfels facies are found. In places, the metavolcanic rocks are cut by a network of quartz veins, pegmatitic and aplitic dikes.

3. 2. 1. FINE GRAINED METAVOLCANICS

The fine grained metavolcanics in the mapped area are composed of slightly metamorphosed rocks and identifiable as basalts, andesites, rhyolites and some tuffs. These rocks are generally grey, green or dark coloured and very fine grained.

These metavolcanic rocks are strongly foliated and form very steep cliffs up to 400 m thickness at the sides of the Suluh river south west of the intrusion. In the eastern part, the unit forms a flat plain and is exposed only at the top. The foliation planes show regular variations in the dip directions indicating that there are some tight minor folds whose hinges are weathered away.

The mineralogy of these rocks is summarized based on petrographic analyses of some selected samples (Samples TG 47, 60, 87 95) and from the work of Kidane (1993) who mapped the adjoining area. The unit is generally low - grade metamorphic rock with plagioclase and quartz porphyroblasts with minor quartz in a recrystallized matrix of

epidote, muscovite and chlorite. The plagioclase is epidotized and sericitized usually partially and in some instances almost entirely. The plagioclase is a main rock forming mineral, but the presence of epidote and chlorite which ranges from 10 to 60 volume % respectively gives the rock its characteristic green colour. Accessory minerals include apatite, sphene, zircon, pyrite and magnetite.

In thin sections, these rocks exhibit distinct alignment of very fine - grained aggregates of epidotes, quartz, sericites and chlorites. Some of the muscovites and quartz show fragmentation along the traces of foliation. Some samples from the aureole also contain garnets indicating a bit higher grade metamorphism due to thermal metamorphism.

The mineral assemblage indicates that the protolith are possibly basalts, andesites or where the quartz is dominant possibly dacites and rhyolites.

The fine grained metavolcanics which form a contact aureole of a few tens of meters width, and those which occur as roof pendants are pervasively epidotized and qualify as greenstones. Contact metamorphism which are superimposed over the previous regional metamorphic effect, resulted in hornfelsic textures which partially obliterated the regional foliation. The aureoles are locally metamorphosed to hornblende - hornfels facies. In some parts, the contact aureole is characterized by pervasive silicification. When at direct contact with dioritic rocks, the roof pendants show migmatite like textures and some exhibit very tight microfolds and crenulation cleavages oriented nearly perpendicular to the regional foliation.

3. 2. 2. METABRECCIAS

The metabreccia dominantly outcrops in the western side of the granitoid intrusion along the Suluh River. Kidane (1993), who mapped eastern side documented its occurrence along stream cuts.

The metabreccias commonly show shades of brown, green and occasionally black, and consist of highly brecciated but silicified and compacted blocks of metavolcanics of various sizes ranging from a few mm to 10 cm and sometimes much bigger diameters (Plate 3.1.)

The fragments which make up the metabreccias are dominantly composed of euhedral to subhedral quartz, plagioclase (altered to epidote and sericite) as phenocrysts, and quartz and sericite as groundmass. Iron oxides are also present as accessory phase.

In the Negash area metabreccias occur subparallel to the western contact of the pluton. The individual blocks are elongated along the same trend. This may lead to suggest that the metabreccias are highly silicified breccias which resulted from the major brittle deformation in the area (see the Geological Map) and subsequent silicification by solutions from the pluton. The presence of some less silicified metabreccias far to the west away from the intrusive contact supports this conclusion.

3. 2. 3. PORPHYROBLASTIC METAVOLCANICS

This unit is exposed in some localities within the contact aureole. These are porphyroblastic metavolcanics and consist of garnet, epidote, chlorite and albite.

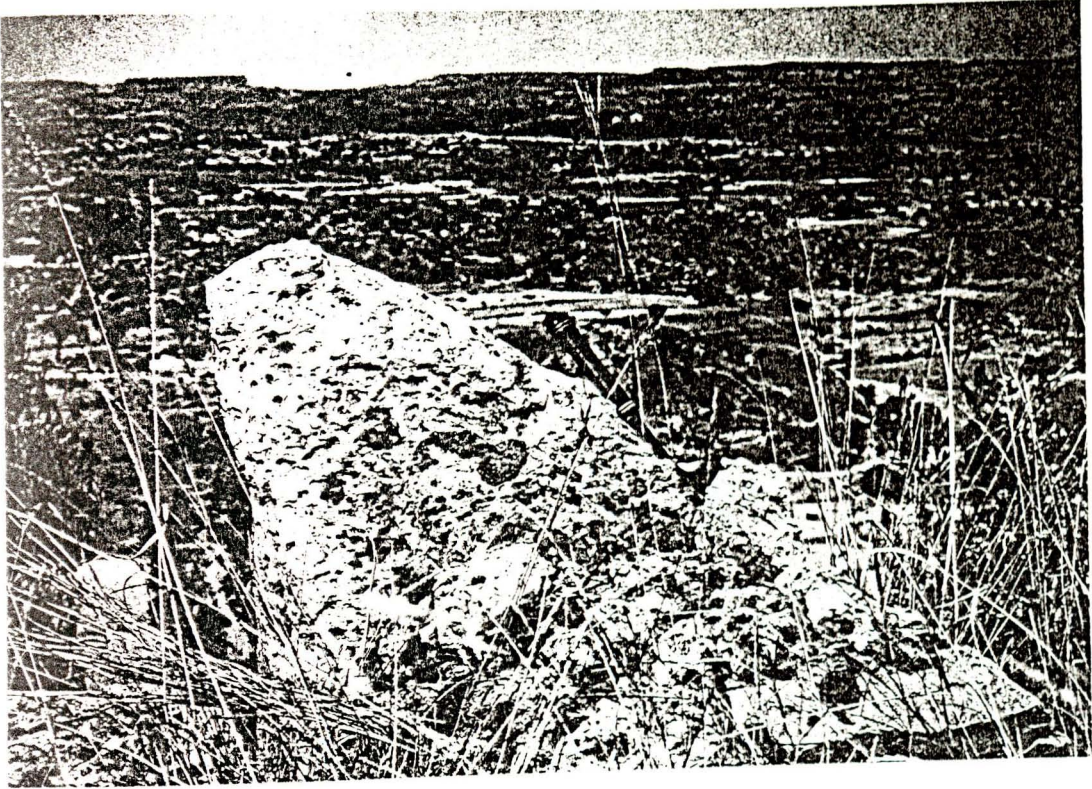


Plate 3. 1. A metabreccia, composed of big clasts which are elongated in one direction.

In most cases, the rocks form spotted schists of reddish to brownish coarse biotite and garnet. The mineral assemblage indicates a hornblende - hornfels facies metamorphism.

The porphyroblastic metavolcanics away from the contact are of greenschist facies metamorphism. Kidane (1993) described the protoliths for these metavolcanic rocks as diabase of hypabyssal origin, even though no evidences were found in this study that supports this conclusion. These rocks (Sample TG 63, 71, 115,125) contain plagioclase phenocrysts ranging in diameter from 1.5 - 2 cm, commonly exhibiting albite and albite-carlsbad twinning. Large quartz grains up to 3 cm also occur with blastoporphyratic texture and enclose many minerals including epidote, chlorite and sericite. Zircon, sphene, apatite, pyrite and magnetite occur as accessory minerals.

3. 2. 4. METASEDIMENTS

The intercalated metasediments (Samples TG 79, 82, 118) within the metavolcanics are represented by thinly bedded, greenish slate and black greywacke. The greywacke is composed of quartz, plagioclase, epidote and sericite, and some accessory minerals like zircon and apatite.

Other lithologies include argillaceous sandstones cemented by calcite, or sericite - chlorite schists of pelitic origin. The latter are characterized by very fine grained aggregates of quartz, feldspar, sericite, chlorite, and epidote.

The metasediments are proportionally subordinate with respect to the metavolcanics.

3. 3. THE NEGASH PLUTON

The Negash granitoid stock is an almost circular body of 8 km diameter and about 50 sq. km outcrop area. The intrusion is not affected by any deformation since no clear evidence of foliation is observed in the granitoid rocks near the contact.

The granitoid intrusion has often a sharp contact with the metavolcanics. The granitoid cuts the foliation direction of the country rocks.

The nature of the western contact, however, is much different from the remaining part. First, the contact becomes almost straight and oriented north east - south west at about 10^0 almost parallel to the Suluh River; second, there are two granitoid satellites of very small size elongated parallel to the river direction and the western contact (See the Geological Map); third, the metavolcanics are dominantly represented by metabreccia which are not commonly observed on the other sides. Hence, the western contact is possibly a tectonic contact.

The granitoid body is a complex intrusion formed by different lithologies cropping out subradially towards the centre. Towards the centre are granodiorites which gradationally change to tonalites. The tonalites sometimes have a sharp compositional contact with the diorites, whereas in other places there are no sharp contacts but rather between diorites and tonalites. Granodiorites occur at the center of the pluton at direct contact with the diorite. The stock is cut by numerous aplites, quartz porphyry dikes, quartz and some pegmatitic veins.

3. 3. 1. GRANODIORITES

The largest part of the outcropping granitoid body is constituted by granodiorites.

The granodiorite along the margin is porphyritic with megacrysts of zoned orthoclase up to 2 cm diameter (Plate 3. 2.). In hand specimen, quartz (colourless), alkali feldspar (flesh red), biotite (shiny black) and plagioclases can be easily identified.

In thin section, the granodiorites show heterogranular, subhedral holocrystalline texture with allotriomorphic plagioclase and microcline and interstitial quartz. Myrmekitic texture is also observed. There are subhedral to euhedral crystals of biotite (pleochroic from dark brown to pale brown) and hornblende (pleochroic from green to brown). Biotite and hornblende show occasional poikilitic texture with inclusion of fine grained quartz. No significant alteration exists except for some transformation of hornblende to biotite in some sections. Zircon, apatite and sphene occur as common accessories, with traces of pyrites and magnetites.

Some of the samples (Samples TG 58, 70) show equigranular, coarse - to medium - grained texture. This variety is common away from the contact.

Some samples near to the contact contain a few epidote and muscovite crystals indicating slight alteration.

Modal analysis (based on visual estimate) gives an average composition of quartz (20 %), plagioclase feldspars (50 %), alkali feldspars (10 %) and mafic minerals (15 %). This composition falls within granodiorite field (Streckeisen, 1975).

The granodiorites contain many microgranular mafic enclaves (MMEs) (Plate 3. 3.) which occur in various sizes and shapes. The size ranges from a few mm up to a meter in diameter, and shapes include circular, elongated, elliptical and sometimes irregular. Almost

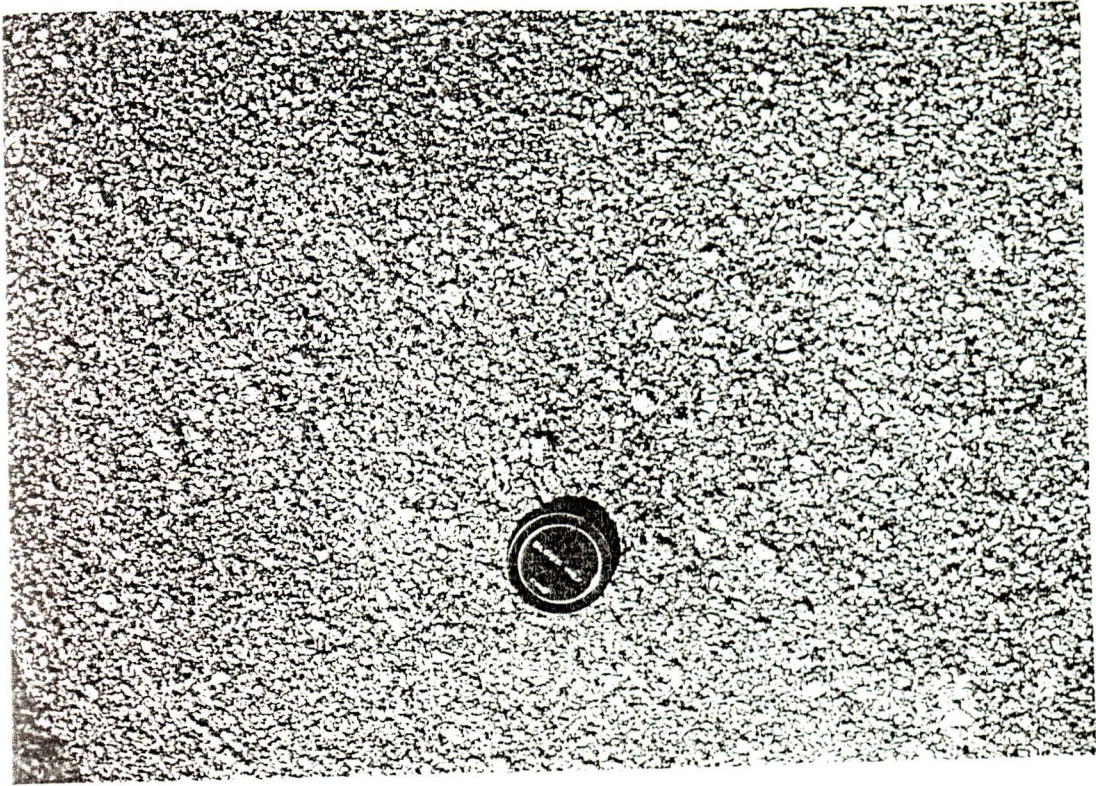


Plate 3. 2. A close view of granodiorite. Big orthoclase grains can be easily recognised.



Plate 3. 3. Granodiorite with microgranular mafic enclave (MME) (darker)

all of the MMEs show dark colour which contrasts with the enclosing mesocratic and occasionally leucocratic granodiorite masses. The MMEs have similar composition with the adjoining diorites, and some are porphyritic with amphibole phenocrysts. Crenulated or quenched margins within the host rock are observed. The MMEs sometimes show assimilated margins. All these textural features agree with the widely accepted hypothesis that MMEs represent blobs of mafic magmas injected into the more acidic granodioritic melts (e.g. Didier and Barbarin, 1991).

In addition to MMEs, there are some xenoliths that show metamorphic fabric. These are obviously fragments torn from wall rocks and caught in the granitoid magma during ascent.

The granodiorites at the margin are cut by aplitic and some pegmatitic dikes and quartz veins oriented nearly parallel to the contact with the country rocks. Within the stock, there are some roof pendants of hornfelsic texture.

The granodiorite shows no considerable structural feature except for occasional alignment of the magmatic minerals. But all the granodiorite peaks within the stock are affected by a very conspicuous hammock (horizontal) jointing.

There are no any indications for the presence of faulting or shearing within the stock but the nature of the western contact may indicate some faulting in the country rocks near the contact.

3. 3. 2. TONALITES

The tonalites show gradational boundary with the granodiorites and are more melanocratic and contain more plagioclase, hornblende and biotite.

The tonalite has similar textural feature as the granodiorite. The modal analysis of the tonalites gives an average composition of quartz (10 %), plagioclases (70 %), K - feldspars (5 %), Hornblene and biotite (15 %). Apatite, sphene and zircon are accessory minerals.

The tonalite (e. g. TG 48) is phanerocrystalline with plagioclase and quartz forming the larger crystals and some microcline. Plagioclase commonly exhibit oscillatory and normal compositional zoning with albite twinning. Some plagioclase contain fine - grained micas that resulted in sieve texture. The microcline is commonly distinguished by clear albite and tartan twinning. The quartz grains show embayment texture along their boundaries with plagioclase. Biotite and hornblende occur as aggregates and rarely as euhedral crystals.

The tonalites close to the granodiorites are frequently capped by highly indurated and thermally baked cap rocks, and form very thick masses of horizontally and vertically jointed blocks. The tonalites contain large MMEs up to 30 cm in diameter, and are frequently cut by aplites of thickness up to 20 cm and of various orientations.

The tonalites MMEs which are sometimes angular blobs and others show rounded features. At the contact, the tonalites are protruding into the diorite and form complexly mingled structures.

3. 3. 3. DIORITES

The diorite and quartz diorite form a massive curved ring-shaped outcrop within the granitoid stock surrounded by granodiorites and tonalites, and occasionally capped by the roof rocks which are migmatitic at the contact.

The diorites show systematic variation in composition and texture. There is a general gradation from fine grained to coarse grained varieties towards the centre, and four types of diorites can be recognized :

1. fine grained, biotite rich diorites cut by microdioritic dikes,
2. coarse grained, quartz diorite,
3. coarse grained, porphyritic diorite with hornblende and biotite phenocrysts,
4. mingled (transitional) diorites of both aphyric and porphyritic types.

At the contact with tonalites, there are some diorite enclosed by tonalites. At the contact with the central granodiorite the diorites are characterized by assimilation features and mingling between mafic and felsic compositions (Plate 3. 4.).

The diorite is also cut by a network of microdiorite, aplite (Plate 3. 5.), pegmatite, granitic and quartz veins (Plate 3. 6.). In the western part of the pluton, the country rocks are cut by fine grained diorites which exhibit chilled margins, and in turn, are cut by many coarse diorite dikes of 30 cm to 1 m thickness generally oriented at N 40⁰ E.

Hornblende, biotite, quartz and sometimes pyrite crystals are distinguished from diorite handspecimens of the coarser varieties. In thin sections (Samples TG 49, 52), the diorites exhibit hollocrystalline, fine - grained to porphyritic texture with coarse subhedral and rare euhedral phenocrysts of biotite and hornblende, and dominant plagioclase feldspars which are commonly zoned. Perthitic intergrowth are sometimes present. Augite, biotite and hornblende show intergrowths while some augites show lammelar or embayment texture. Quartz usually occurs as accessory except in some samples of quartz diorites where it constitutes up to 10 %.

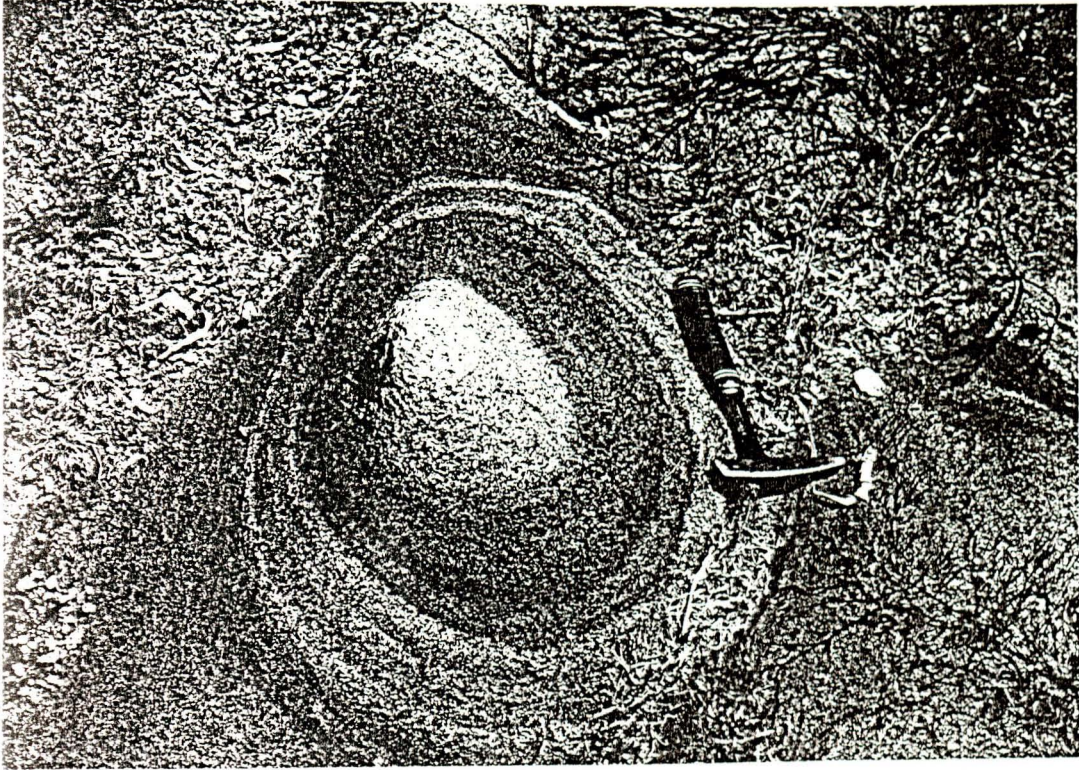


Plate 3. 4. Assimilation between mafic (darker) and felsic phases at the contact zone.

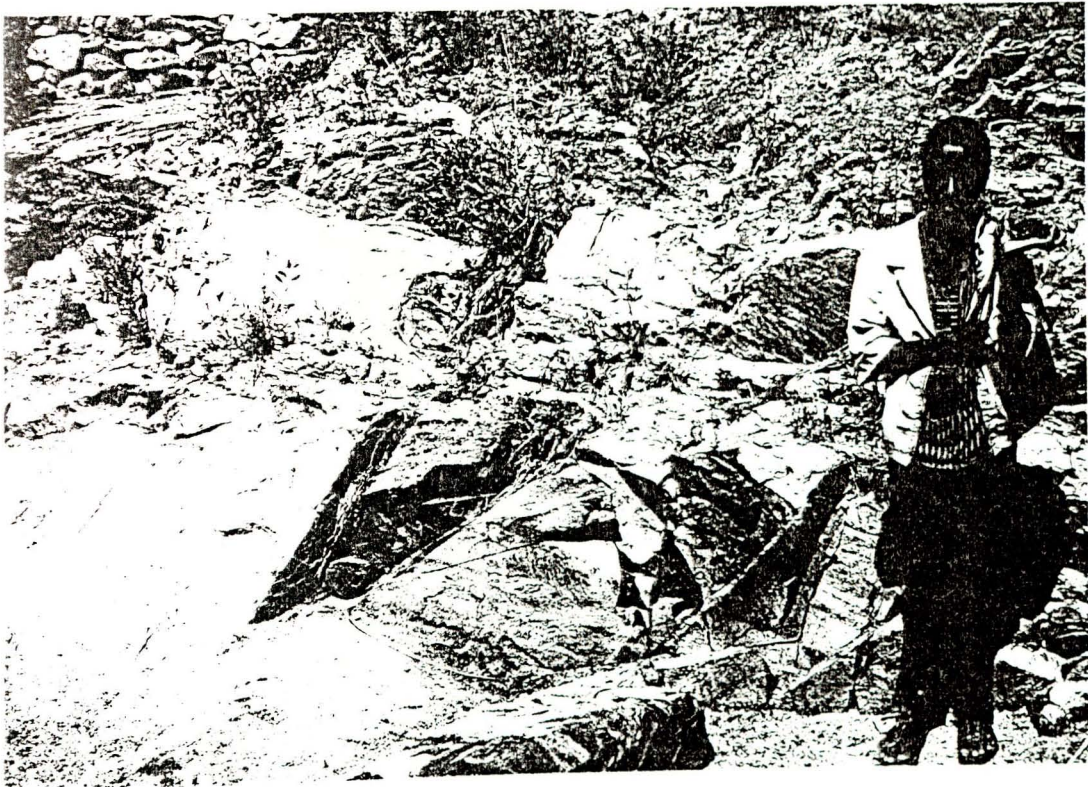


Plate 3. 5. A microdiorite dike (dark) cutting the roof pendants.

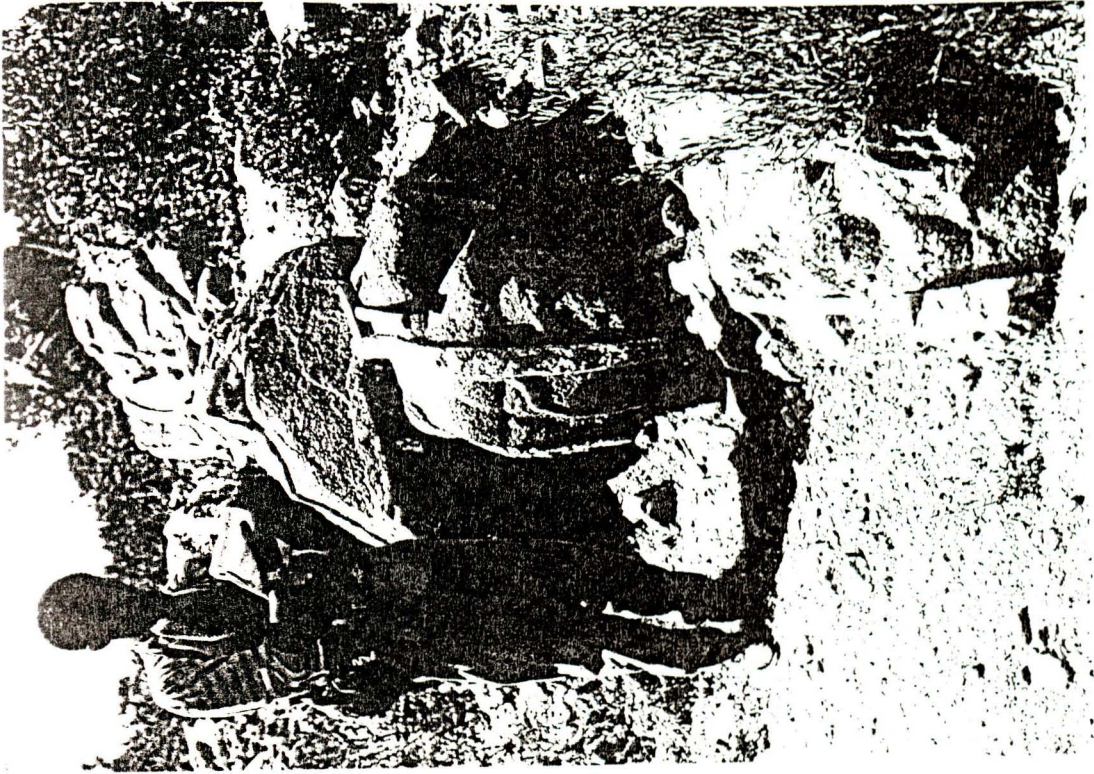


Plate 3. 6. Set of quartz and pegmatite veins (light) crossing tonalites near the contact to the diorites

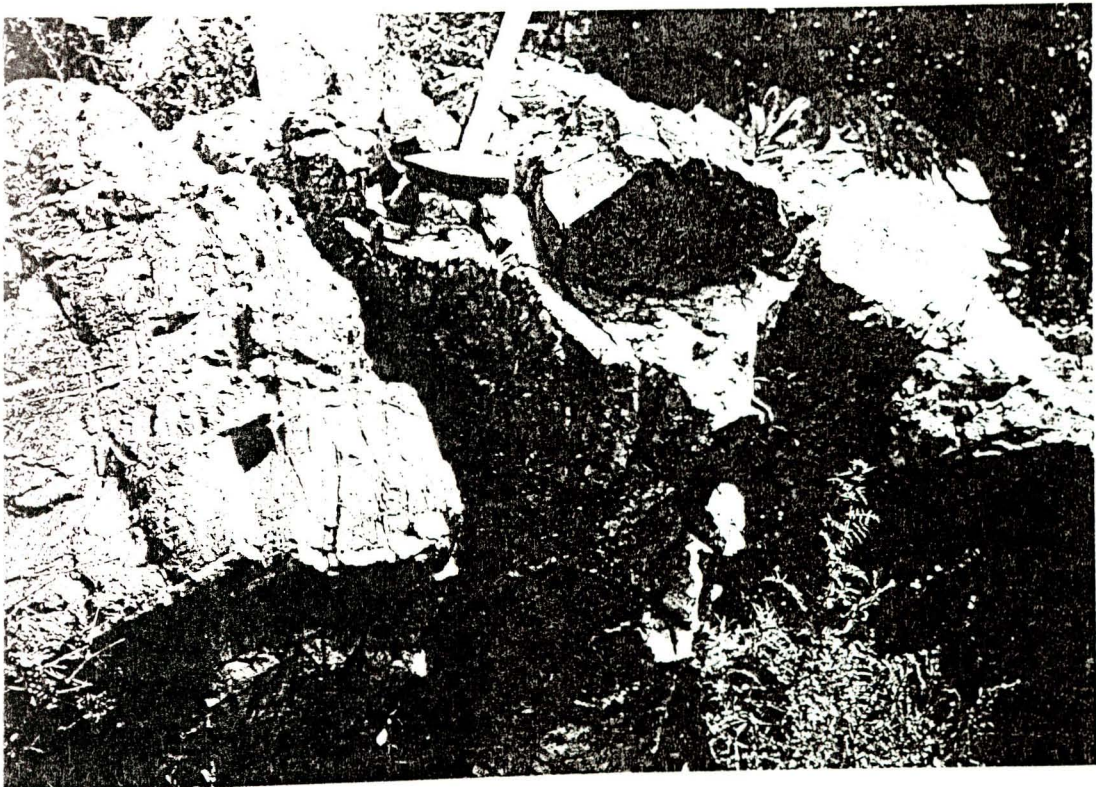


Plate 3. 7. An aplite dike crossed by quartz veins

The average mineralogical composition of these rocks is given by plagioclase (40 %), biotite (25 %), hornblende (20 %), augite (10%), quartz (4 %), with negligible K - feldspars, which fall in the diorite field (Streckeisen, 1975). However, there are some diorites which are pyroxene rich and can be termed as pyroxene diorites while the majority of the diorites are represented by biotite - hornblende diorites. The common accessories are sphene, zircon and traces of opaque minerals. The latter form micrographic and skeletal grains.

3. 3. 4. QUARTZ PORPHYRY DIKES

The country rocks near to the contact with the pluton are cut by a series of quartz porphyry dikes which have a general orientation of N10° E to almost N - S and are subparallel to the foliation direction of the metavolcanic rocks. These dikes are common in the eastern and western parts of the pluton.

The quartz porphyry dikes are 3 to 12 m thick and extend for a considerable distance along the strike. Some of the quartz porphyry dikes are finer grained at their contact with the host rocks and are commonly affected by a swarm of quartz veins and veinlets generally oriented perpendicular to the orientation of the dikes. In some localities the dikes are surficially stained by epidotes from the country rocks.

The dikes are composed of quartz, feldspar and very fine groundmass with visible quartz, orthoclase and plagioclase phenocrysts. In thin section (e. g. Sample TG 99), the rocks exhibit porphyritic textures with coarse plagioclase lath and quartz set in fine - grained muscovite, quartz and K - feldspar. Biotite occurs as scattered anhedral crystal. Zircon

occurs as accessory along with opaque minerals including cubic pyrite. The studied samples indicate that the dikes are of intermediate composition.

3. 3. 5. APLITE DIKES

Aplite dikes are widespread near the contact zones of the pluton. The thickness of the dikes ranges from a few cm to 2 m within the pluton and up to 20 m in those cutting the metavolcanics along the western contact. The aplite dikes are subparallel to each other and to the foliation direction of the metavolcanics. In some, the dikes cut the foliation of the host rocks. In places, the aplites form lens - like bodies.

Most of the aplite dikes are cut by a network of quartz veins and veinlets (Plate 3. 7.), and are composed of very fine grained quartz and feldspar crystals with some pyrites while others are microgranular in texture. In thin section (Sample TG 53, 112), the aplites are commonly represented by very fine - grained aggregates of quartz and K - feldspars which show micrographic intergrowths. There are some anhedral to subhedral biotite and muscovite. There are pyrite crystals and zircons as accessories. The aplites which are composed of subequal proportions of quartz and K - feldspars with little plagioclase, muscovite and biotite fall in the granite field (Streckeisen, 1975), indicating that they represent hypabyssal granites.

In addition to the quartz porphyry and aplite dikes, there are pegmatite and quartz veins in the area.

3. 3. 6. STRUCTURE OF THE NEGASH PLUTON

Observation carried out during field work are helpful for the aim of understanding the structure and the intrusion level of the Negash granitoid body. In synthesis:

1. The horizontal jointing commonly observed in the plutonic rocks (Plate 3. 8. and 3. 9.), especially in the granodiorites indicate that the outcropping rocks represent the upper part of the intrusive body. This is confirmed by the presence of patches of roof pendants in several parts of the pluton (Plate 3. 10).
2. The presence of granodiorites both at the margin and center of the pluton with similar composition suggest that these rocks belong to a single magmatic event.
3. The presence of MMEs in both the granodiorites and tonalites suggest that the dioritic magma was intruded into the upper part of the granitoid body later than the formation of granodiorites and tonalites.
4. The mingled structures at the contact between different rock types testify that the intrusion of mafic magma occurred when the tonalites and granodiorites were still in a partially or totally molten state.
5. The presence of aplitic, microgranitic and pegmatitic dikes represent late stage differentiates of the residual magma. The residual magma filled fractures related to volume contraction of the magma body.
6. The felsic dikes also cut through the wall rocks.



Plate 3. 8. Granodiorite affected by prevalent horizontal (hammock) jointing



Plate 3. 9. Closer view of horizontally jointed granodiorites

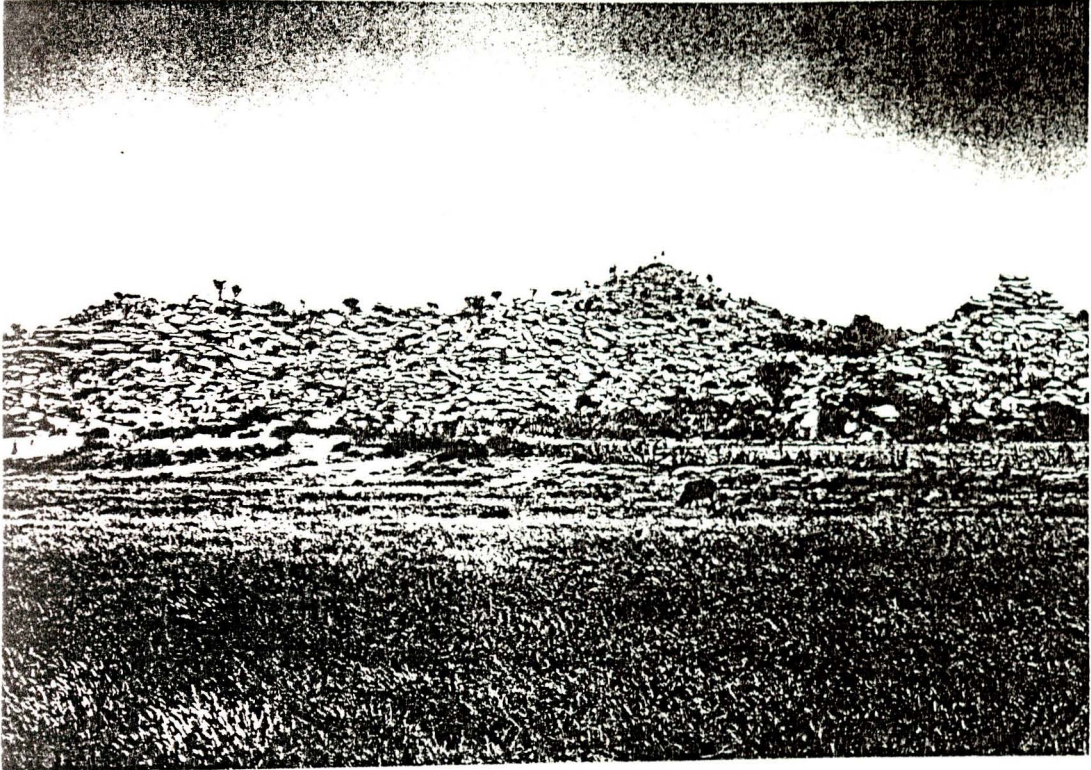


Plate 3. 10. Roof pendants (back ground) over the jointed granodiorites

In conclusion, the overall picture which emerges from the field observations is that of a compositionally zoned intrusive body. This was formed by an upper felsic rocks and a mafic lower part. During intrusion, the more fluid and hotter mafic magma pierced through the upper felsic compositions of the partially crystallized granodiorites and tonalites. Mafic magma mingled with the granodiorites and in some zones. This resulted in the development of several mafic enclaves inside granodiorites and tonalites and of mingled zones at the contact between various rock types.

The most important implication of this model is that the Negash intrusion is not an ring complex, as it could be inferred from the surface outcrops, but a differentiated calc alkaline pluton in which the mafic rocks are dominant. The stages of development of this intrusion is represented in Fig. 3. 2.

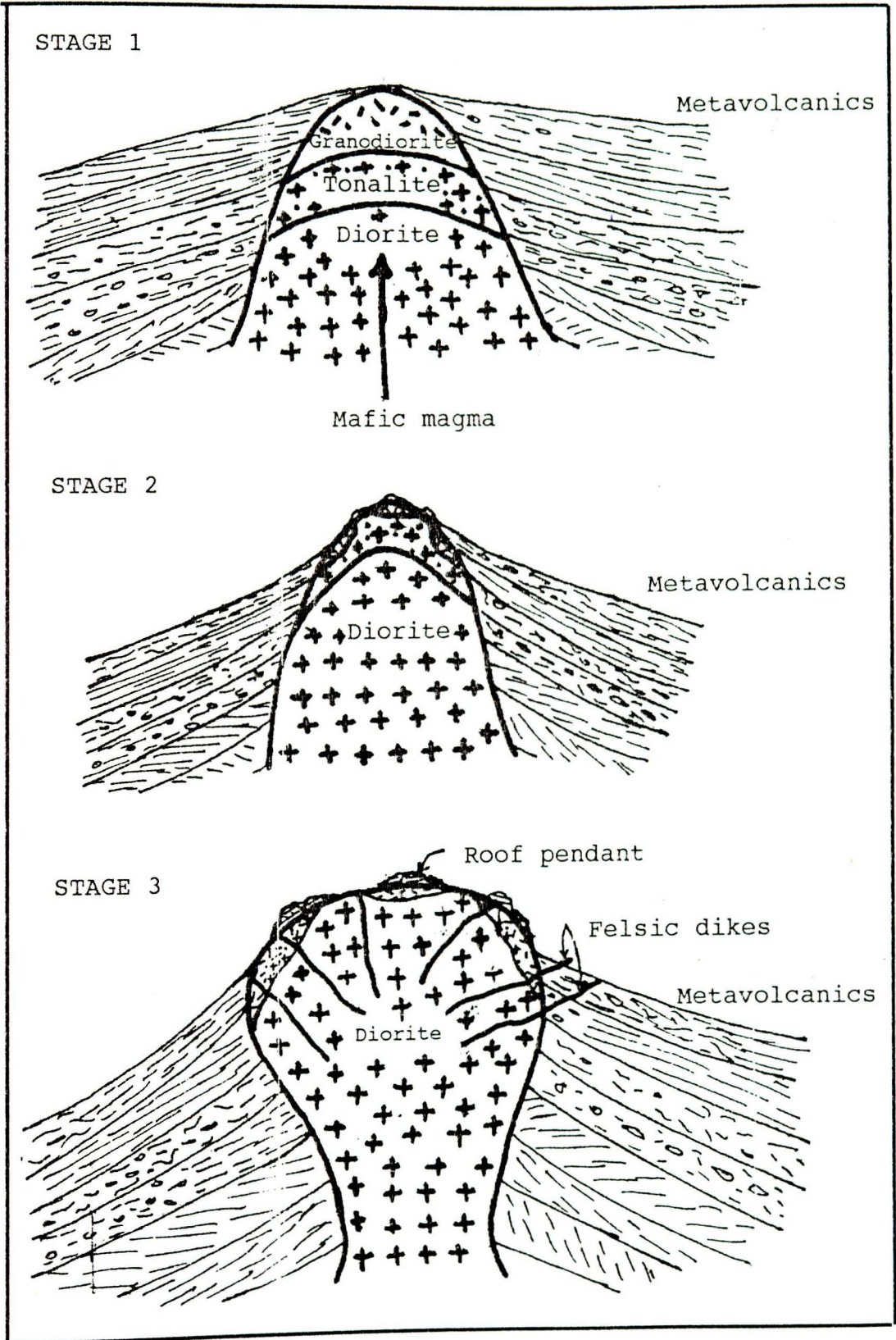


Fig. 3. 2. Stages of development of the Negash pluton

CHAPTER 4

METAMORPHISM AND STRUCTURAL GEOLOGY

4. 1. METAMORPHISM

The granitoid stock is not affected by metamorphism except for a slight epidotization along its contact with the country rocks. Instead, the intrusion resulted in thermal metamorphism of the country rocks, which superimposed on the preexisting regional metamorphism. The foliation of the country rocks at the contact is obliterated by migmatite-like features.

The contact metamorphism is restricted to the very narrow contact aureole around the granitoid body and to the contact between the granitoid body and the roof pendants. The regional metamorphism is a characteristic feature of the country rocks. In some places, it is possible to clearly recognize the superimposition of the contact metamorphic effect over the preexisting regional metamorphic effect.

4. 1. 1. REGIONAL METAMORPHISM

Although no attempt was made to study the detailed metamorphic nature of the metavolcanics in the field, some samples collected from the country rocks and the roof pendants were petrographically studied and revealed some important features.

The studied samples reveal the mineral assemblages listed below :

Plagioclase + quartz + microcline + sericite (TG 95)

Quartz + microcline + plagioclase + muscovite + sericite + epidote + chlorite

(TG 82)

Quartz + epidote + sericite \pm microcline

Quartz + muscovite + sericite \pm microcline \pm plagioclase. (TG 79)

These identified mineral assemblages are of greenschist facies, affecting volcanic rocks ranging in composition from rhyolite to basalt and some sedimentary rocks of argillaceous sandstone and pelitic rocks.

The fine grained metavolcanic rocks show mineral alignment representing traces of foliation or planar surface of the rocks. The fine - grained aggregates are made up of intimate intergrowths of quartz, epidote, chlorite, or quartz, sericite, chlorite, which enclose rare larger crystals of quartz, muscovite, plagioclase or microcline, around which fine - grained aggregates deflected from the general foliation trend.

The porphyroblastic metavolcanics and metabreccias are weakly foliated and are characterized by having relict porphyritic texture where quartz and plagioclase represent the phenocrysts. These are enclosed within fine - grained aggregates of quartz, chlorite, epidote and sericite. The quartz and plagioclase are disposed in such a way that they define the general foliation surface. Quartz shows straining along the foliation. Muscovite and microcline occasionally occur as blastoporphyratic, and they sometimes exhibit blastopoklitic and perthitic textures, respectively. The plagioclase displays albite and carlsbad twinning; this can be partially due to the metamorphic effect (Spry, 1969).

The metasediments are represented by some pelitic and argillaceous sandstones which are metamorphosed to sericite - chlorite schists. Some of the metasediments are

affected by dynamic metamorphic effect as can be observed from the straining of the quartz and muscovite crystals in the rocks.

4. 1. 2. CONTACT METAMORPHISM

The contact metamorphic effect resulted in the formation of the contact aureole. The aureoles are represented by metavolcanics except for the western contact where there are metabreccias with no evident contact metamorphism.

The studied samples from the contact revealed the following mineral assemblages :

Plagioclase + quartz + monocline + muscovite + epidote \pm biotite (TG 120)

Quartz + plagioclase + epidote + chlorite (TG 47)

Quartz + muscovite + sericite \pm plagioclase \pm chlorite (TG 63)

Garnet + epidote + quartz + plagioclase + microcline \pm muscovite \pm chlorite
(TG 125)

Epidote + sericite + quartz \pm chlorite \pm biotite (TG 60)

Garnet + hornblende + quartz + plagioclase

The mineral assemblages indicate that the contact metamorphism is of the albite-epidote hornfels facies. The regional metamorphic effect is superimposed by the later contact metamorphism, resulting in hornfelsic texture which obliterated the pre - existing foliation.

In some places within the contact aureole and in the roof pendants, the contact metamorphic effect of the granitoid intrusion resulted in partial melting of the country rocks, resulting in migmatite - like structures (Plate 4. 1.).

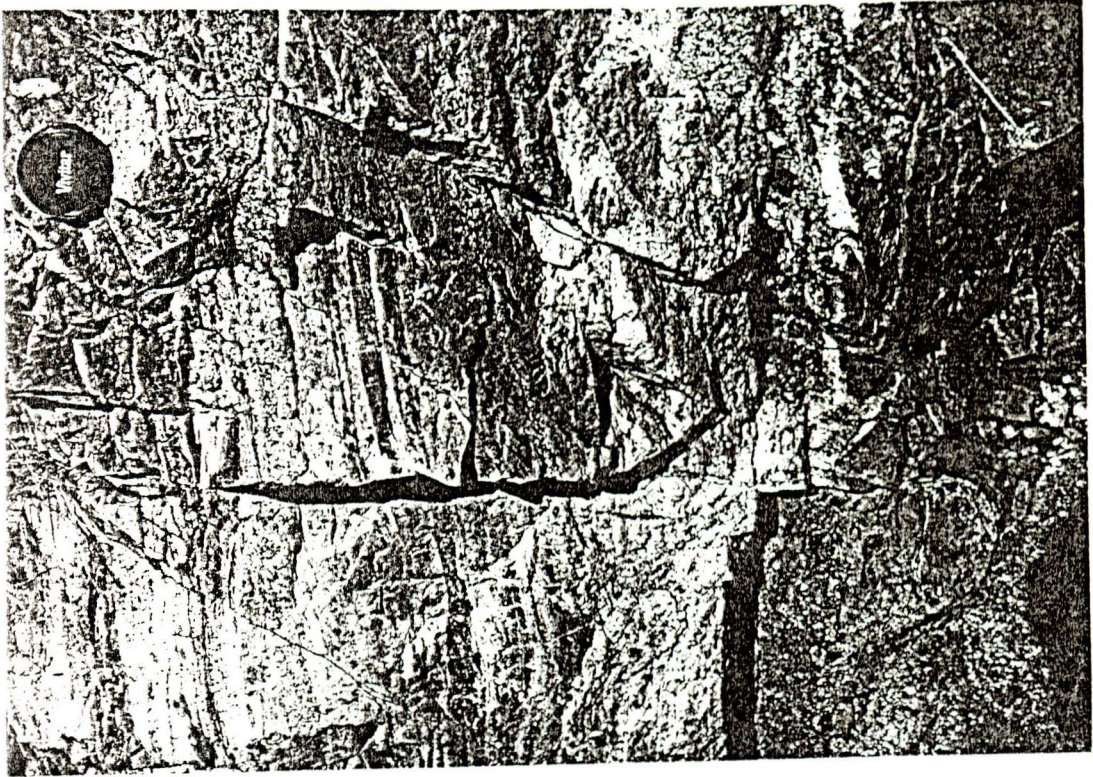


Plate 4. 1. A roof - rock partially melted and compacted due to the effect of thermal metamorphism.

This process occurred essentially where the country rocks are in contact with dioritic rocks. Sometimes contact metamorphism has been obliterated by later silicification.

The mineral assemblage for some metavolcanics indicates that there is a local higher grade metamorphism of hornblende - hornfels facies. These effects are restricted to some places at the contact aureole and to the roof pendants. This hornblende - hornfels facies metamorphism is best represented along the southern contact where there is a highly foliated amphibolite rock oriented at $N30^{\circ} E$ which is composed of different layers that are rich in coarse garnet crystals, fine shiny garnets, and coarse quartz crystals with little garnets, in addition to the dominant hornblende. Some roof pendants are also characterized by similar mineral assemblages.

These rocks are characterized by relict porphyritic crystals of quartz, plagioclase and microcline which are set in fine - grained matrix of granoblastic quartz, that is aggregated with epidote and chlorite which also show intimate intergrowth. The quartz are generally strained while the plagioclases are twinned and the microclines are perthitic. The garnets are coarse grained and exhibit dendritic crystal growth structures, enclosing many quartz and plagioclase. In some cases garnets show intergrowths with those minerals.

4. 2. STRUCTURAL SETTING

The general structural framework of the region (including the present study area) was outlined by Beyth (1971), Garland (1980) and Levitte (1970), and a detailed structural and tectonic features of the Negash Synclinorium were given by Kidane (1993). These authors

suggested that the region is characterized by a series of synclinoriums and anticlinoriums arranged in an en echelon manner from West to East.

The present study area is located within the "Hauzien Recumbent Anticline" (Beyth 1971) and is bounded by the Bereh anticlinorium to the West and the Negash Synclinorium to the East.

The anticlinal nature of the country rocks in the present study area is recognized by the oppositely dipping directions of the foliations representing the opposing limbs of an anticline whose hinge was eroded away possibly because of the uplifting related to the granitoid intrusion. The roof pendants may represent remnants of the country rocks at the vicinity of the hinge of the preexisting anticline.

In the present investigation, no attempt was made to study the structure of the region, because it is beyond the scope of this study. But the structural frame work of the intrusion and the country rocks were investigated based on satellite imagery, aerial photo and field work.

The investigation revealed that the granitoid intrusion is unaffected by any major structure except the fault lineament along its western contact, while the country rocks are affected by a series of faults at various orientations.

4. 2. 1. FAULTS

The granitoid stock which is circular in nature shows rather linear contact with the metavolcanic rocks along the western margin. This is clearly identified from satellite imagery and aerial photograph and fault controlled major river of the region. In addition, the

western contact is represented only by diorites with no granodiorites, while there are two small granodioritic satellites that are sub parallel to the contact. This indicates that the granodioritic bodies were emplaced possibly along the plane of weakness created by the fault or reactivated older fault. But the later hypothesis seems to be more plausible because such old normal faults are common in the region and extend for about 70 - 80 km along the strike with a considerable throw some times reaching up to several hundred meters like the one in the Negash Synclitorium. Such faults are younger than the folding events (Beyth 1971). So the granitoid stock was intruded along either the axial plane of the anticlinoriums or reactivated normal fault. This is strongly supported by the dominance of brecciated rocks in the vicinity which resulted from the effect of the older fault and subsequently silicified under the effect of temperature and circulation of fluids related to the granitoid intrusion.

Apart from this conspicuous fault line, the remaining part of the granitoid stock is massive, except some minor displacements, fractures and joints.

The country rocks on the other hand are affected by a series of normal faults with two major orientations :

1. NNE - SSW trending faults which are almost parallel to the foliation direction of the country rocks. The magnitude of vertical displacement can not be determined. The faults are evident from the resulting parallel ridges elongated along the regional structural grain, each ridge representing a faulted block. These faults belong to the Precambrian faults which are part of the regional fault structure of the Mozambique orogeny (Kazmin, 1972)
2. WNW - ESE trending normal faults which are only common in the southern and southwestern part of the mapped area. These faults have a throw of up to 30 m,

generally dipping towards the south (Plate 4. 2.) and are subparallel to the “Wukro Fault Belt” which separated the “Mekele Outlier” from the Precambrian rocks (Plate 4. 3). These faults cut the NNE - SSW ridges in an en echelon manner. The Suluh River, which generally flows north - south subparallel to the NNE - SSW trending faults, sometimes changes direction to WNW-ESE where it encounters the similarly oriented faults. The WNW - ESE faults are much younger than the Precambrian faults.

The country rocks are also characterized by minor faults, fractures and joints.

In conclusion, the major structural and metamorphic sequence of events in the region are:

- Regional metamorphism of the country rocks accompanied by tight folding, resulting in the series of anticlinoriums and synclinoriums (Beyth, 1971),
- Faulting along NNE - SSW direction of the country rocks
- Faulting along WNW - ESE direction of the country rocks,
- Intrusion of the granitoid body along an older NNE - SSW striking normal fault, accompanied by contact metamorphism of locally hornblende - hornfels facies at the contact, and late uplifting,
- Weathering and erosion of the roof rocks and surfacing of the Negash granitoid stock.



Plate 4. 2. WNW - ESE trending fault (dipping south) South of the Negash pluton close to the contact.

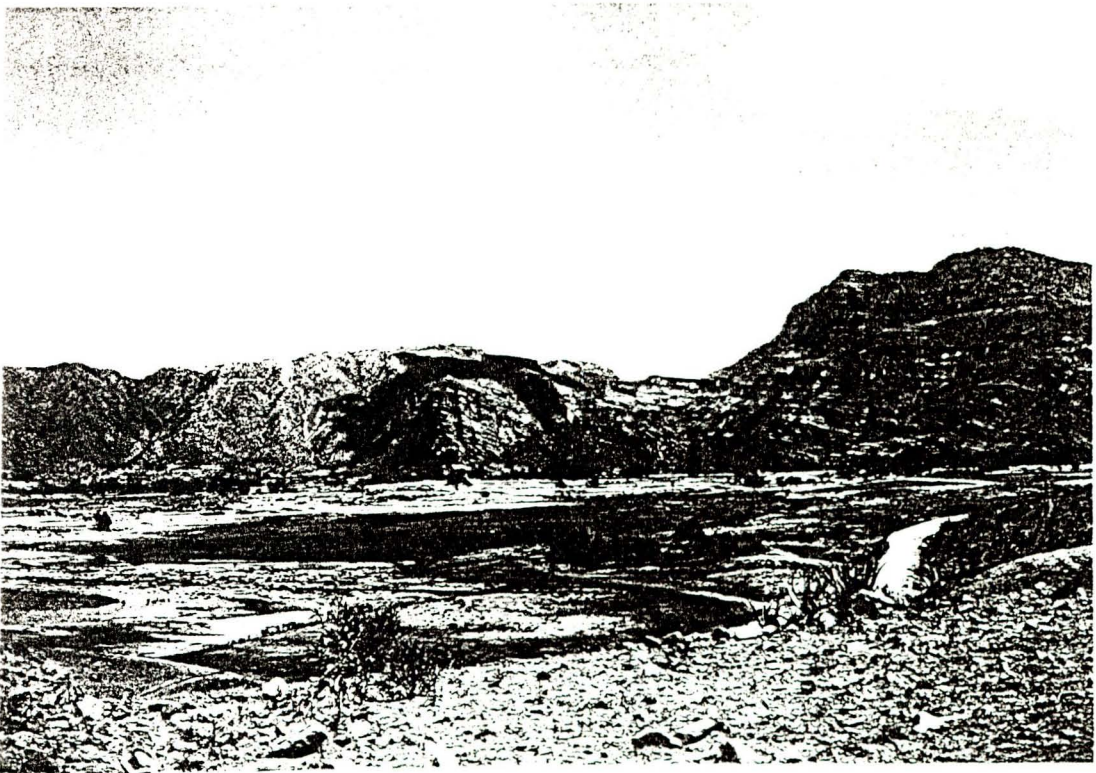


Plate 4. 3. The fault contact between Tsaliel group (left) and the Adigrat sandstone (right), which marks the "Wukro fault belt".

CHAPTER 5

GEOCHEMISTRY

5. 1. GENERAL

A total of 84 samples were collected from the pluton, the country rocks and from the Suluh river sediments of which 38 samples are from various parts of the country rocks. The remaining 41 samples are from the granodiorites, tonalites, diorites, quartz porphyry dikes, aplites, pegmatites and quartz veins; three stream sediment samples and two barite veins have been collected.

The Negash pluton is almost circular and sampling was done from the contact towards the centre along five traverses which are at proportional distance from each other; the sampling was also directed at representing the various lithologic types and their relative proportion.

Hand specimen were crushed by steel jaw crusher and reduced to pea size and pulverized to fine powder using an agate mortar or disc mill. A total of 66 samples were geochemically analyzed. The results are treated using the geochemical software IGPETWIN, which helped to plot many variation and discriminant diagrams. The plots were discussed in order to shed light on the origin, tectonic setting and composition of the various rocks and their mutual genetic relationships.

5. 2. GEOCHEMISTRY OF THE METAMORPHIC ROCKS

5. 2. 1. SAMPLING AND ANALYTICAL METHODS

Almost all the metamorphic rock samples came from areas near to the contact with the plutonic body, except for a few samples which were taken from areas away from the pluton. Only trace elements and selected major elements have been analyzed. Based on the available data and trace element relationship the composition of the protoliths and the tectonic setting of their emplacement is inferred.

A total of 34 metamorphic rock samples were analyzed for 3 major elements (CaO, Na₂O and FeO) and 25 trace elements by Instrumental Neutron Activation Analysis at the Activation Laboratories, Lancaster, Ontario, Canada. About 30 g of powdered rock sample was irradiated in a nuclear reactor for one hour. Measurements of gamma ray activity has been carried out at different times after irradiation, in order to measure the activity of both short-lived isotopes (e.g. Na) and long-lived isotopes (e.g. REE). The precision of the obtained analytical data is variable as a function of the concentration of the elements and of the nuclear characteristics of the various nuclides. For the concentrations twice above detection limits, precision is better than 10, except for Rb, Sr, Ca, Sn, Ni which show several analytical problems with the INAA method. For these elements, the data must be considered as semiquantitative. The obtained analytical data, together with the detection limit for each element are given in Table. 5.1. Some of the trace elements including Ag, Ir, Hg, and Cs invariably show concentrations below their respective detection limits, whereas others like Ni, Mo, Sr, Ta are above detection limits only for a few samples.

TABLE 5. 1. (A) GEOCHEMICAL DATA FOR SAMPLES FROM THE METAMORPHIC ROCKS

Elements	Ca	Fe	Na	Ba	Co	Cr	Cs	Hf	Mo	Ni	Rb	Sb	Sc	Sn	
Units	%	%	%	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	
DetN.limit	1.4	0.027	0.06	100	100	5	10	2	1	5	50	30	0.2	0.1	100
TG 46	0.5	4.2	2.45	710	-5	19	-2	11	6	-50	71	0.4	7.7	200	
TG 47	8.4	9.08	5.78	-100	15	140	-2	5	-5	67	-30	-0.2	44	300	
TG 56	16.8	5.46	3.38	660	10	91	-2	4	-5	-50	-30	-0.2	14	200	
TG 62	-1	4.51	6.74	-100	-5	12	-2	8	-5	-50	-30	0.4	14	300	
TG 63	-1	7.98	2.49	880	17	120	2	4	-5	-50	-30	-0.2	23	200	
TG 71	11.2	8.47	4.37	2000	7	100	-2	3	-5	-50	-30	0.9	28	200	
TG 72	7	13.06	5.16	390	27	110	-2	3	-5	-50	-30	0.8	31	200	
TG 75	-1	3.5	6.18	270	-5	-10	-2	12	-5	-50	69	-0.2	7.4	200	
TG 76	-1	2.59	6.74	270	-5	-10	-2	11	-5	-50	-30	-0.2	4	200	
TG 77	14	8.69	1.25	-100	-5	33	-2	7	-5	-50	-30	0.4	17	200	
TG 79	5.6	5.71	1.7	710	12	46	3	3	-5	-50	75	0.8	14	100	
TG 81	2.8	3.51	3.53	370	7	19	2	4	-5	-50	52	0.4	8.4	100	
TG 82	4.2	6.05	5.07	530	11	24	-2	4	-5	-50	-30	-0.2	13	100	
TG 83	-1	9.33	5.29	-100	29	87	-2	3	-5	-50	-30	1	32	200	
TG 86	-1	11.28	6.43	510	9	29	-2	7	-5	-50	90	-0.2	18	200	
TG 87	-1	2.73	0.84	300	-5	46	-2	5	-5	-50	61	0.3	2	200	
TG 88	-1	5.74	0.51	710	-5	16	-2	11	-5	-50	140	2	6	200	
TG 89	-1	3.98	0.75	1800	-5	15	-2	9	-5	-50	210	6.9	7.7	200	
TG 90	-1	4.17	0.07	170	-5	27	-2	2	-5	-50	43	0.6	1.9	100	
TG 92	-1	4.54	3.33	410	-5	53	-2	7	-5	-50	120	1.8	9.6	100	
TG 93	-1	2.96	2.17	970	-5	15	-2	10	-5	-50	190	0.9	6	100	
TG 95	-1	11.29	0.23	1100	5	110	4	6	-5	-50	120	0.6	24	200	
TG 96	-1	5.08	3.74	340	10	130	2	3	-5	-50	-30	-0.2	14	100	
TG 98	-1	4.55	1.32	280	7	12	-2	6	-5	-50	41	0.5	19	100	
TG 100	-1	11.61	2.15	-100	48	110	-2	3	-5	-50	-30	1.4	39	200	
TG 102	-1	7.32	2.32	610	14	93	-2	5	-5	-50	74	-0.2	22	100	
TG 106	-1	4.09	4.31	2200	-5	15	-2	12	-5	-50	67	-0.2	9	100	
TG 115	-1	5.05	0.77	950	-5	100	2	6	-5	-50	81	-0.2	25	100	
TG 116	2.8	4.96	1.9	490	-5	59	-2	4	-5	-50	60	-0.2	16	100	
TG 118	-1	4.34	3.56	390	-5	48	-2	4	-5	-50	44	-0.2	13	100	
TG 120	-1	3.53	5.46	790	7	43	-2	5	-5	-50	-30	-0.2	5.8	100	
TG 124	-1	3.62	5.16	960	7	44	-2	5	-5	-50	-30	0.3	5.9	100	
TG 125	-1	6.51	6.33	-100	7	15	-2	8	-5	-50	-30	0.4	18	100	
TG 127	-1	4.53	3.99	1100	-5	23	2	10	-5	120	62	0.6	20	100	

TABLE 5.1(A) CONTD.

Elements Units	Sr %	Ta PPM	Th PPM	U PPM	Zn PPM	La PPM	Ce PPM	Nd PPM	Sm PPM	Eu PPM	Tb PPM	Yb PPM	Lu PPM	Au PPB	As PPM
Detn.limit	0.05	1	0.5	0.5	50	1	3	5	0.1	0.2	0.5	0.05	0.05	3	2
TG 46	-0.05	-1	5.4	1.8	-50	26	64	38	7.6	1.7	1.4	8.6	1.5	-3	-2
TG 47	-0.05	-1	-0.5	-0.5	-50	6	21	17	3.8	1.4	0.5	4.2	0.76	-3	-2
TG 56	-0.05	-1	3.4	-0.5	-50	14	34	14	4	0.9	0.9	3.3	0.56	-3	-2
TG 62	-0.05	-1	2.5	-0.5	-50	5	18	16	2.5	0.8	0.9	5.1	0.85	14	-2
TG 63	-0.05	-1	2.8	2.4	-50	22	50	25	5.1	1.6	0.7	4.3	0.64	8	-2
TG 71	-0.05	1	-0.5	-0.5	-50	8	23	10	3.8	1.6	0.7	2.8	0.59	-3	3
TG 72	-0.05	-1	-0.5	-0.5	-50	9	26	19	4.2	1.9	0.7	3.5	0.6	-3	-2
TG 75	-0.05	-1	8	2.6	-50	9	31	10	2.8	0.9	0.5	4.3	0.85	-3	-2
TG 76	-0.05	-1	4.4	1.9	-50	21	47	25	6.2	1.6	1	8.5	1.39	-3	-2
TG 77	0.07	-1	2.9	1.9	74	39	70	46	8.6	2.4	1.4	8	1.33	-3	2
TG 79	-0.05	-1	1.6	-0.5	60	12	29	19	2.8	1	0.7	1.8	0.35	7	-2
TG 81	-0.05	-1	1.9	-0.5	-50	13	22	17	2.6	0.7	0.5	1.7	0.37	-3	-2
TG 82	-0.05	-1	2.1	-0.5	-50	11	25	9	2.5	0.9	0.5	1.6	0.27	-3	-2
TG 83	-0.05	-1	-0.5	-0.5	125	7	18	14	2.4	0.8	0.8	2.2	0.43	-3	-2
TG 86	-0.05	-1	2.2	-0.5	450	8	23	16	3.1	0.6	0.5	5.6	1.01	8	-2
TG 87	-0.05	-1	3.2	0.9	80	15	40	24	5	0.7	0.5	3.5	0.65	-3	-2
TG 88	-0.05	-1	6.4	1.8	-50	84	180	89	18	2.6	2.3	10.8	1.77	-3	-2
TG 89	-0.05	-1	4.7	1.7	-50	20	52	27	6.1	1.1	1.2	8	1.31	-3	6
TG 90	-0.05	-1	0.9	-0.5	-50	5	11	-5	1.5	0.5	0.5	1.3	0.26	-3	-2
TG 92	-0.05	-1	2.9	-0.5	-50	9	24	13	2.9	0.7	0.5	5.3	0.96	8	-2
TG 93	-0.05	-1	4.1	1.8	88	13	37	23	4.8	1	1	8.9	1.56	-3	-2
TG 95	-0.05	-1	6	2.7	-50	33	85	35	9.6	3.1	1.8	7.4	1.31	-3	-2
TG 96	-0.05	-1	2	-0.5	-50	9	22	11	2.4	0.8	0.5	2.2	0.42	-3	2
TG 98	-0.05	-1	0.9	-0.5	64	13	40	24	5.9	1.6	1	6.1	1.07	-3	-2
TG 100	-0.05	-1	-0.5	-0.5	250	26	50	30	7.6	3.1	1.2	4.8	0.76	8	-2
TG 102	-0.05	-1	3.8	-0.5	109	8	23	13	2.8	0.9	0.5	4.3	0.71	7	-2
TG 106	-0.05	-1	4.5	2.3	-50	20	55	28	6.8	1.6	1.4	8	1.35	-3	-2
TG 115	-0.05	2	4.3	1.7	102	30	60	32	6.8	1.3	0.8	4	0.73	5	-2
TG 116	-0.05	-1	2.4	-0.5	78	14	31	17	3.8	1	0.5	3.4	0.63	-3	-2
TG 118	-0.05	-1	3	1.6	94	10	22	12	3.9	1	0.5	3.9	0.67	-3	13
TG 120	-0.05	-1	3.7	-0.5	-50	21	36	19	3.3	1.1	0.5	2.5	0.39	6	4
TG 124	0.12	-1	4.4	1.7	-50	22	46	16	3.6	1.2	0.5	2.5	0.4	-3	4
TG 125	-0.05	-1	3	2.5	-50	20	49	35	7.7	2	1.3	7.5	1.12	4	-2
TG 127	-0.05	-1	3.6	1.4	-50	28	64	28	7.8	1.5	1.1	8.1	1.41	-3	-2

TABLE 5. 1. (B) GEOCHEMICAL DATA FOR SAMPLES FROM THE NEGAH PLUTON (ANALYSED BY INAA)

Elements	Ca	Fe	Na	Ba	Co	Cr	Cs	Hf	Mo	Ni	Rb	Sb	Sc	Sn
Units	%	%	%	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
Detn.limit	1.4	0.027	500	100	5	10	2	1	5	50	30	0.2	0.1	100
TG 48	7	5.67	4.21	1100	16	93	3	5	-5	350	-30	-0.2	13	300
TG 49	0.5	10.77	2.91	850	30	330	-2	5	-5	56	-30	-0.2	18	200
TG 50	0.5	0.94	3.5	550	-5	15	-2	4	-5	-50	-30	-0.2	1.4	200
TG 51	0.5	1.13	0.64	-100	-5	35	-2	-1	-5	-50	-30	-0.2	0.4	100
TG 52	9.8	12.42	2.6	540	37	470	-2	3	-5	56	-30	-0.2	23	200
TG 53	-1	1.63	4.03	460	-5	25	-2	4	9	-50	-30	-0.2	2.1	200
TG 57	-1	1	3.61	450	-5	25	-2	3	17	-50	94	-0.2	0.8	200
TG 58	-1	3.67	3.76	880	10	72	-2	4	-5	-51	-30	-0.2	7.4	200
TG 61	-1	7.61	0.52	780	15	120	3	5	-5	-50	87	-0.2	26	200
TG 64	8.4	11.82	3.29	670	25	18	-2	4	-5	-50	-30	-0.2	16	200
TG 65	-1	1.05	2.98	1400	-5	21	-2	2	7	-50	-30	-0.2	1.5	100
TG 66	-1	1.61	3.83	790	-5	-10	-2	3	-5	-50	-30	-0.2	1.5	200
TG 73	-1	1.08	3.99	-100	-5	11	-2	4	-5	-50	95	-0.2	1.2	100
TG 99	-1	2.41	3.02	1100	-5	12	-2	5	-5	-50	-30	-0.2	3	100
TG 104	-1	5	4.05	890	15	160	-2	4	-5	-50	81	-0.2	11	100
TG 110	8.4	11.78	2.99	2400	35	300	-2	4	-5	-50	-30	-0.2	22	100
TG 111	-1	6.89	0.09	310	-5	20	-2	-1	-5	-50	-30	0.2	0.9	100
TG 112	-1	0.91	7.15	440	-5	16	-2	4	7	-50	-30	-0.2	4.3	100
TG 114	-1	1.5	3.82	460	-5	11	-2	7	-5	-50	-30	-0.2	14	100
TG 121	2.8	4.77	3.62	750	17	170	-2	4	-5	-50	65	-0.2	11	100

TABLE 5. 1 (B) CONTD.															
Elements	Sr	Ta	Th	U	Zn	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Au	As
Units	%	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPB	PPM
Detn.limit	0.05	1	0.5	0.5	50	1	3	5	0.1	0.2	0.5	0.05	0.05	3	2
TG 48	-0.05	-1	2	-0.5	155	26	64	30	5.1	1.4	-0.5	1.6	0.39	-3	-2
TG 49	-0.05	-1	2.5	2.8	185	30	66	37	6.7	2.8	-0.5	1.3	0.3	-3	-2
TG 50	-0.05	-1	12	5	119	10	11	-5	0.4	-0.2	-0.5	0.5	0.07	-3	-2
TG 51	-0.05	-1	1.9	-0.5	-50	6	8	-5	0.4	-0.2	-0.5	0.3	0.05	-3	-2
TG 52	-0.05	-1	-0.5	-0.5	-50	26	66	44	8.8	2.8	-0.5	2.3	0.37	-3	-2
TG 53	-0.05	-1	10	1.1	-50	20	21	-5	1.1	0.4	-0.5	0.5	0.07	-3	-2
TG 57	-0.05	-1	14	3.7	-50	39	48	19	0.7	-0.2	-0.5	1.5	0.23	-3	-2
TG 58	0.2	-1	2.9	-0.5	-50	19	46	21	2.5	1.1	-0.5	0.9	0.19	-3	4
TG 61	0.08	-1	3.5	1.9	200	15	37	15	3.6	0.9	0.7	3.6	0.65	-3	-2
TG 64	0.11	-1	0.9	-0.5	169	35	89	48	9.5	3.7	1.2	2.4	0.46	-3	-2
TG 65	-0.05	-1	6.1	-0.5	-50	8	11	-5	0.5	-0.2	-0.5	0.7	0.11	-3	-2
TG 66	-0.05	-1	6.6	-0.5	-50	21	28	12	0.9	0.4	-0.5	0.5	0.08	-3	-2
TG 73	-0.05	-1	16	4.2	-50	5	6	-5	0.2	-0.2	-0.5	0.8	0.14	-3	-2
TG 99	-0.05	-1	8	2.1	89	38	72	31	3.8	1.1	-0.5	0.8	0.16	-3	-2
TG 104	-0.05	-1	2.4	-0.5	99	17	42	25	3.4	1.1	-0.5	1.3	0.28	-3	-2
TG 110	-0.05	-1	1.4	-0.5	-50	21	49	24	5.5	2.2	0.6	1.6	0.27	-3	-2
TG 111	-0.05	-1	0.6	-0.5	-50	9	13	12	2.9	0.5	-0.5	1.8	0.27	-3	3
TG 112	-0.05	3	3.8	3.9	-50	3	9	-5	0.9	-0.2	-0.5	1	0.23	-3	3
TG 114	-0.05	-1	6.4	2.3	78	37	84	50	11	0.8	1.7	9.9	1.62	-3	3
TG 121	0.13	-1	3.3	1	-50	21	44	21	3.4	1.1	-0.5	1.4	0.21	-3	2

TABLE 5. 1. (C) GEOCHEMICAL DATA FOR SAMPLES FROM THE NEGASH PLUTON													
(FOR MAJOR ELEMENTS, ANALYSED BY XRF)													
ELEMENTS	Na[2]O	K[2]O	Al[2]O[3]	SiO[2]	CaO	MgO	Fe[2]O[3]	MnO	TiO[2]	P[2]O[5]	LOI		
UNITS	%	%	%	%	%	%	%	%	%	%	%	%	%
TG 48	4.46	2.55	16.08	61.34	3.9	4.38	5.31	0.07	0.8	0.24	0.88		
TG 49	3.09	1.76	13.23	53.62	5.92	7.87	10.45	0.11	2.41	0.83	0.7		
TG 50	3.99	6.27	14.55	73.25	0.35	0.29	0.52	0.01	0.05	0.01	0.72		
TG 51	0.84	0.04	1.58	96.11	0.08	0.42	0.41	0.01	0.08	0	0.43		
TG 52	2.93	0.87	13.36	47.13	8.18	9.74	12.73	0.15	2.98	1.13	0.81		
TG 53	4.84	1.51	13.43	75.24	1.88	0.88	1.4	0.02	0.22	0.04	0.52		
TG 57	3.87	4.6	12.53	76.84	0.68	0.24	0.45	0.01	0.06	0.01	0.72		
TG 58	3.84	3.99	14.31	67.93	2.38	2.63	3.37	0.05	0.49	0.15	0.87		
TG 61	7.21	0.92	15.39	74.37	0.28	0.29	0.44	0.01	0.02	0.09	1		
TG 64	3.77	1.19	15.35	51.97	6.99	5.24	10.8	0.12	2.59	1.35	0.63		
TG 65	3.42	5.89	13.78	74.39	0.42	0.32	0.81	0.01	0.11	0.01	0.83		
TG 66	4.33	1.87	13.46	70.67	1.39	0.67	1.23	0.02	0.19	0.01	6.16		
TG 73	4.6	4.43	13.56	75.53	0.74	0.22	0.44	0.02	0.05	0	0.41		
TG 99	3.4	3.57	15.68	68.58	1.52	1.04	2.63	0.05	0.38	0.09	3.05		
TG 104	4.28	2.65	14.8	64.29	3.15	3.99	4.87	0.07	0.6	0.17	1.13		
TG 110	3.04	1.45	13.32	53.75	6.89	7.38	10.17	0.1	3.31	0.54	0.05		
TG 111 A	2.96	2.3	12.87	55.85	5.31	6.7	9.86	0.11	2.44	0.7	0.9		
TG 111 B	2.61	3.11	12.8	54.07	5.52	7.06	10.57	0.13	2.66	0.68	0.79		
TG 111 C	4.04	2.48	15.69	59.18	3.69	4.89	6.67	0.08	0.8	0.24	2.24		
TG 112	8.41	1.16	11.8	74.8	0.77	0.29	0.47	0.02	0.04	0.02	0.69		
TG 114	5.16	0.21	14.29	78.55	0.77	0.49	1.27	0.02	0.16	0.01	0.61		
TG 121	4.23	2.49	14.31	62.49	3.69	5.56	5.22	0.08	0.77	0.24	0.92		

TABLE 5. 1.(D) GEOCHEMICAL DATA FOR SAMPLES FROM THE NEGASH PLUTON

(FOR TRACE ELEMENTS, ANALYSED BY XRF)

ELEMENTS	Nb	Y	Rb	Zr	Sr	Ni	Cr	V	Ba	La	Ce
UNITS	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
TG 48	15	15	44	108	1467	45	108	107	923	15	40
TG 49	17	20	21	167	849	91	400	183	722	22	49
TG 50	10	1	83	54	254	5	13	5	499	9	10
TG 51	14	2	0	3	40	7	26	6	4	5	10
TG 52	15	29	1	45	1244	123	589	250	421	24	63
TG 53	9	3	20	66	712	5	20	20	334	15	18
TG 57	11	0	73	53	195	5	10	8	208	33	41
TG 59	7	9	65	97	870	25	72	63	978	10	33
TG 61	16	10	17	59	35	4	8	3	55	1	6
TG 64	15	27	5	62	1330	16	30	197	638	27	73
TG 65	10	3	66	46	400	4	13	11	1170	10	10
TG 66	9	2	23	68	723	6	5	16	625	22	33
TG 73	11	0	159	65	76	4	8	3	25	8	4
TG 99	12	9	60	192	301	6	11	39	1168	26	56
TG 104	6	10	61	117	877	55	180	4	655	12	20
TG 110	15	14	15	99	932	87	334	231	1493	14	32
TG 111 A	17	20	32	142	887	65	304	176	868	18	34
TG 111 B	17	22	74	159	846	68	286	183	1047	26	56
TG 111 C	15	6	41	69	1373	46	117	119	962	5	25
TG 112	21	10	0	55	592	4	6	4	356	0	6
TG 121	7	12	61	110	876	81	223	107	578	16	26

5. 2. 2. RESULTS

Major and trace element analysis of the samples whose concentrations are above the detection limit are plotted in variation diagrams, and as chondrite and primordial mantle normalized patterns. The purpose of the plots are several and include i) to display in a graphical form the abundances and variation patterns of the elements; ii) to recognize the distribution patterns of the elements that help understand the original chemical nature of the protolith and the behaviour of the elements during metamorphism and metasomatism.

Binary Variation Diagrams

Variation diagrams of the analyzed elements against Sc are shown in Fig. 5.1. Sc has been used as the abscissa unit because this element is determined with good precision and accuracy with INAA. Sc is also present in variable concentrations in the rocks, both igneous and sedimentary, and displays a general decrease from mafic to felsic composition and from pelitic rocks to sandstones. Finally, Sc enters a wide variety of minerals such as amphibole, chlorite, pyroxene, epidote, etc. which are stable in wide range of metamorphic conditions. Because of the stability of host minerals, Sc is graded as one of the most immobile elements during metamorphism and its concentration is a useful reference value for estimating the behaviour of other trace elements.

Two different symbols have been used for hornfelses and for regional metamorphic rocks in the diagram of Fig. 5.1, in order to discriminate possible variation in the behaviour of the elements during the two types of metamorphism.

In general terms, the most evident characteristics that arise from the data are:

1. There is no significant geochemical difference between the hornfels and regional metamorphic rocks for most of the elements.
2. There is a positive correlation of Sc versus FeO, Cr and Co, in a generally scattered data. Co defines parabolic trend with respect to Sc.
3. Na₂O, CaO, LREE and HREE show a large scattering of data and no significant correlation with Sc. The sample TG 88 shows a very high anomalous concentration for all the REE. This sample was collected in the southern part of the pluton from the highly silicified fault breccia along the Suluh River.
4. Rubidium, Hf, Th and Ba show a poorly defined negative correlation with Sc. High U values are observed in the low-Sc rocks. Moreover, Hf and Rb seem to show two distinct trends in the low-Sc rocks. The highest Ba concentration is found in the hornfels sample from the roof pendants.
5. Zinc, Au, Sn, and Sb show a broad scatter and most of the samples have concentrations below the detection limit.
6. Nickel, Mo, Sr, and Ta are almost always below the detection limit of the analytical method used.

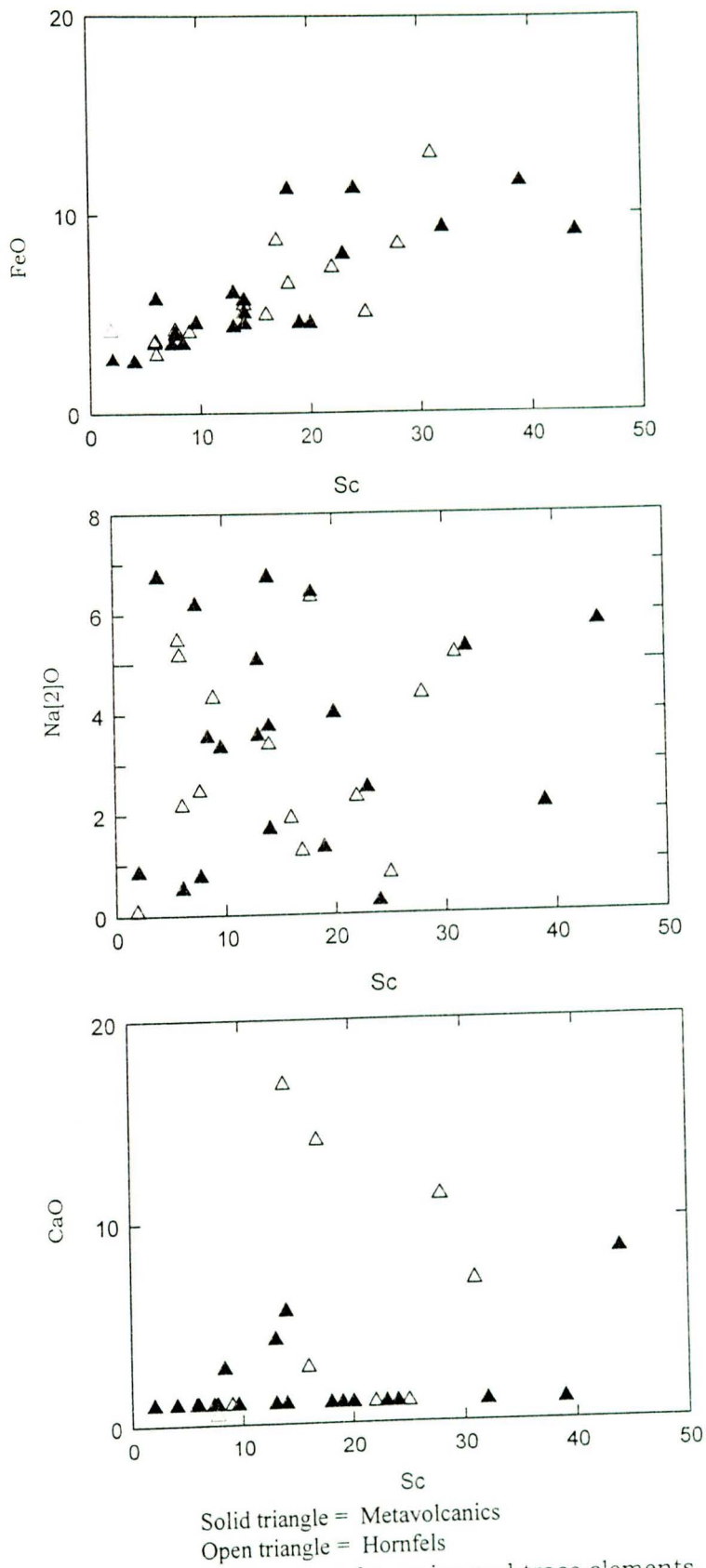
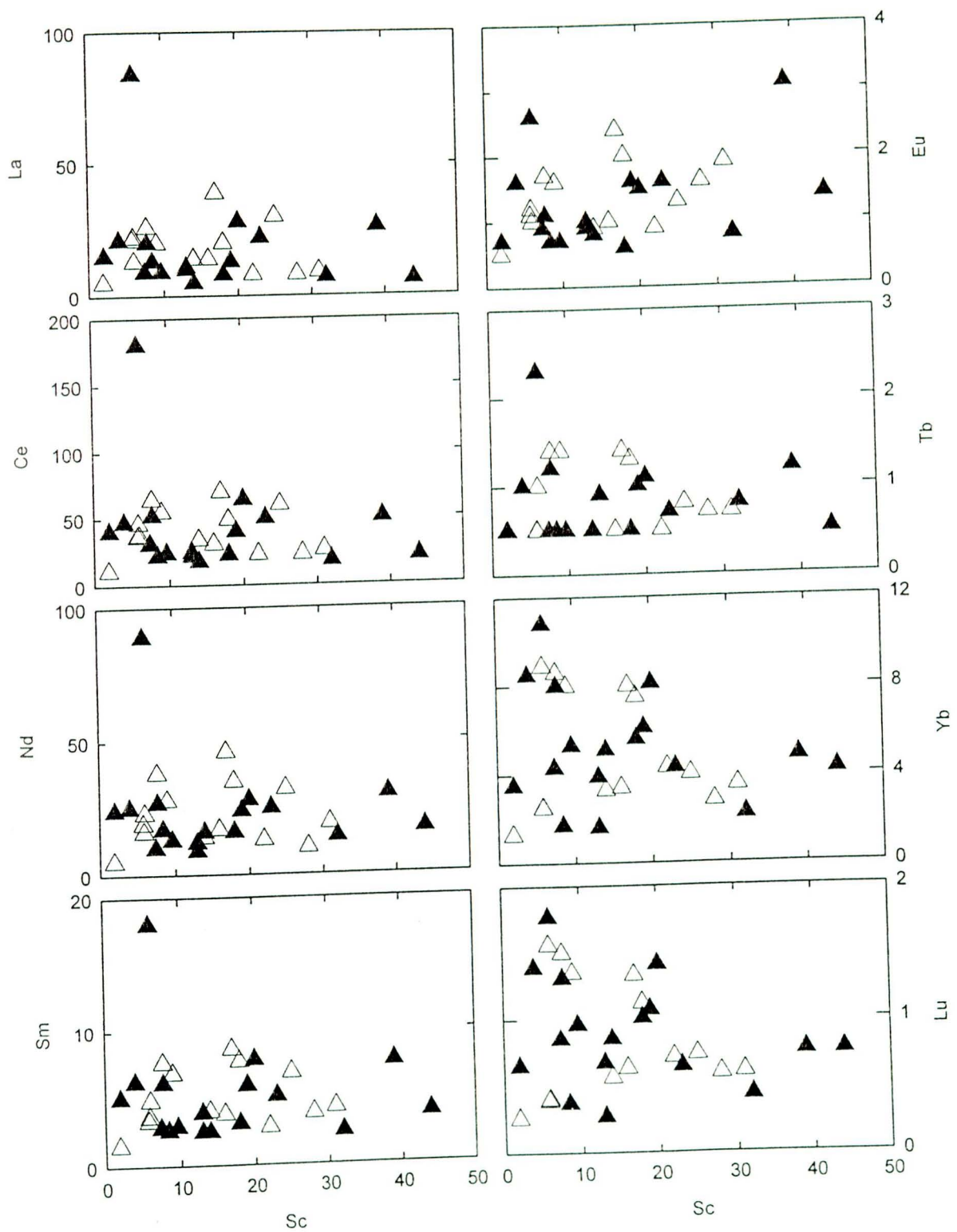


Fig. 5.1. Sc - variation diagrams for major and trace elements



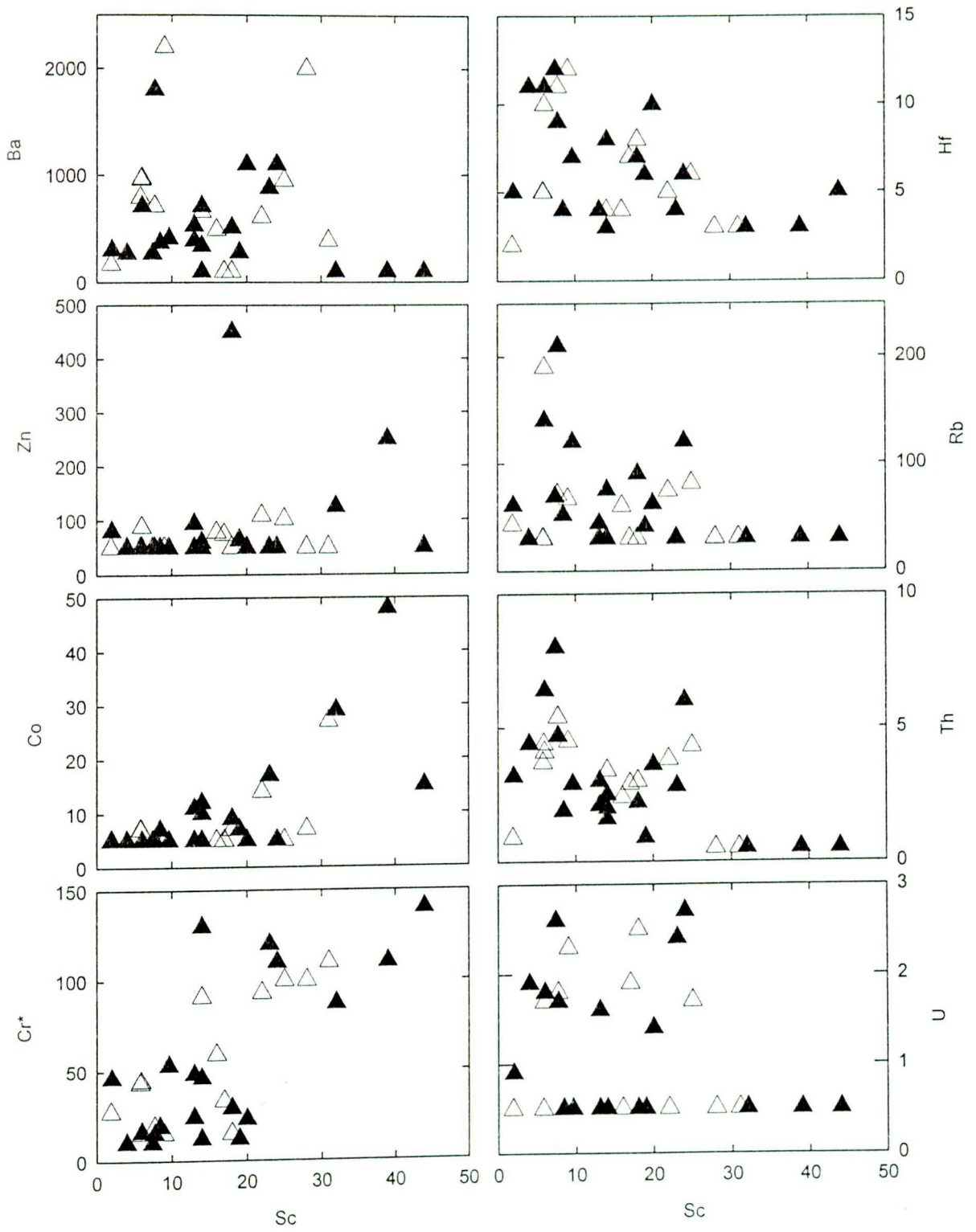


Fig. 5.1. Continued.

REE Patterns

Chondrite normalized REE patterns are shown in Fig. 5.2. The analyzed samples have been divided into three classes on the basis of their Sc contents. The rocks under investigation display variable abundances and fractionation of REE. Some samples have almost flat REE pattern, but the largest number has $(La/Lu)_N > 1$. Many samples have significant negative Eu anomalies. This feature is particularly visible in the samples with less than 10 ppm Sc.

Incompatible Element Patterns

plots normalized to the primordial mantle composition of Wood et al. (1979) of incompatible elements are reported in Fig. 5.3. These diagrams, similar to the REE patterns, are powerful tools to display both the absolute enrichment and the relative fractionation of the elements.

The analyzed samples display several characteristics in common. These include:

1. A moderate overall fractionation of incompatible elements with a fairly high ratio between most incompatible and least incompatible elements (i.e. Rb/Tb_N ; Ba/Tb_N around 10)
2. Positive Ba spike in many samples, a feature that is more evident in the high-Sc samples.
3. Negative anomaly of Ta, which, as mentioned, is always below the detection limit of 1 ppm.

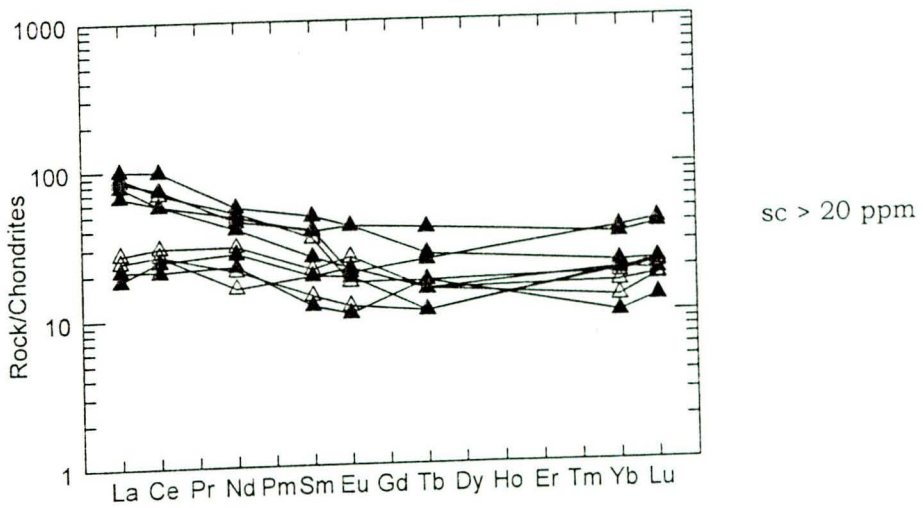
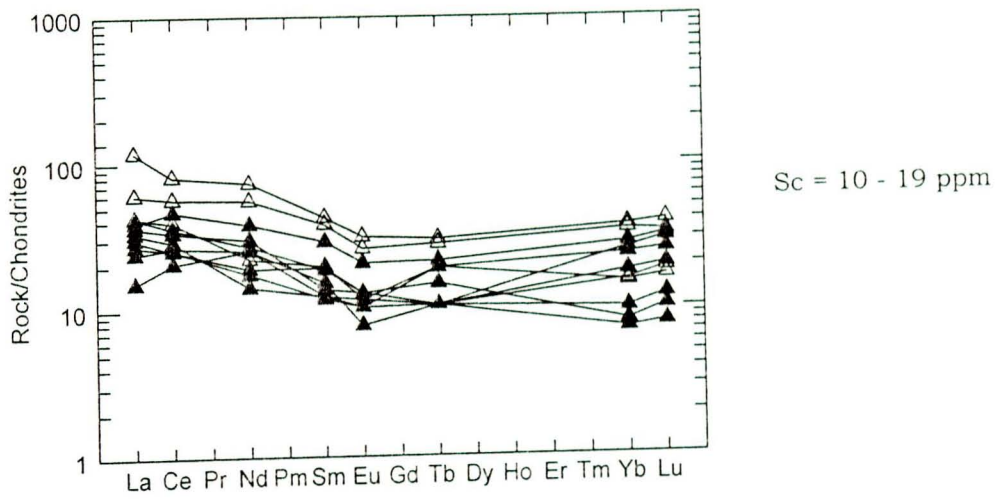
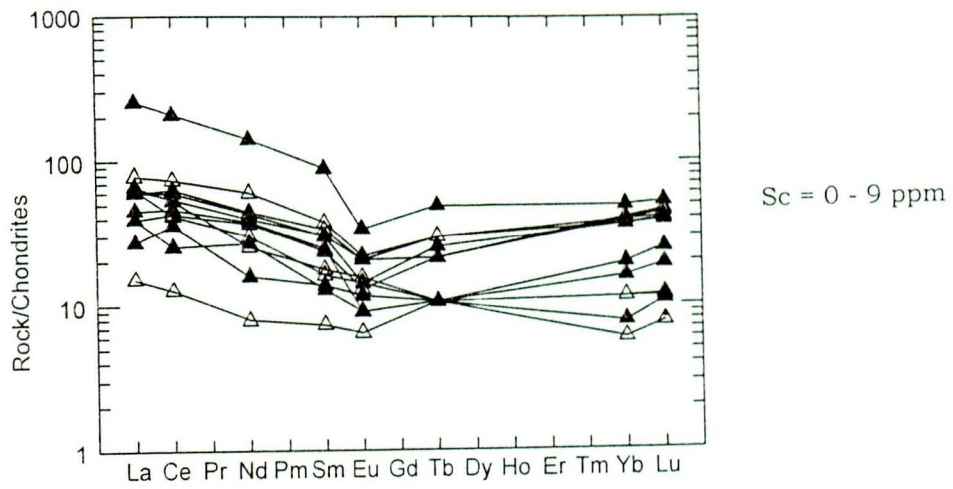
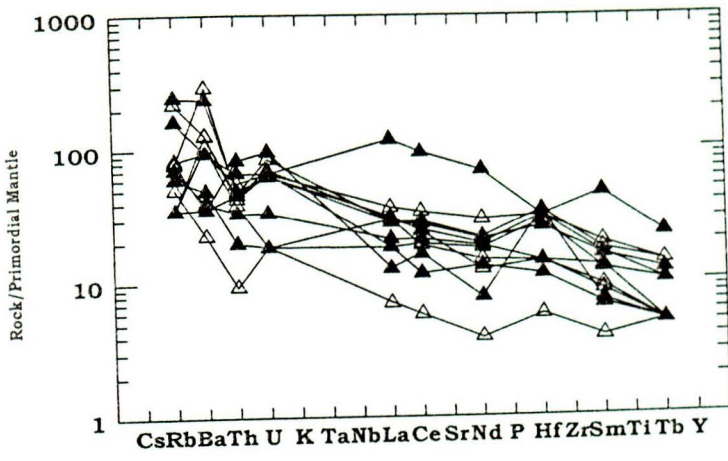
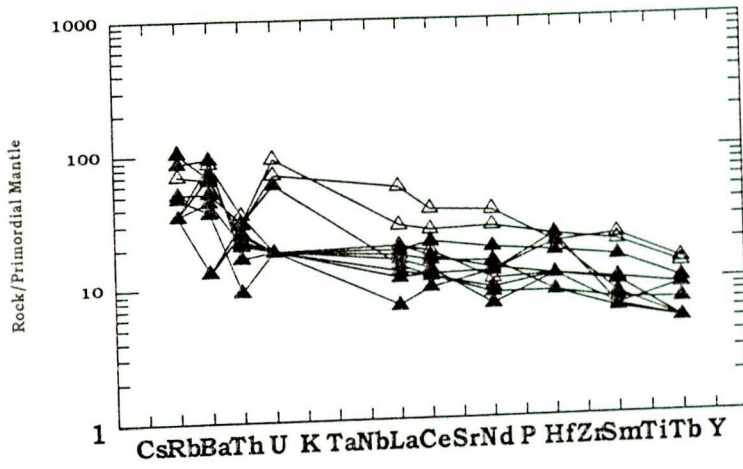


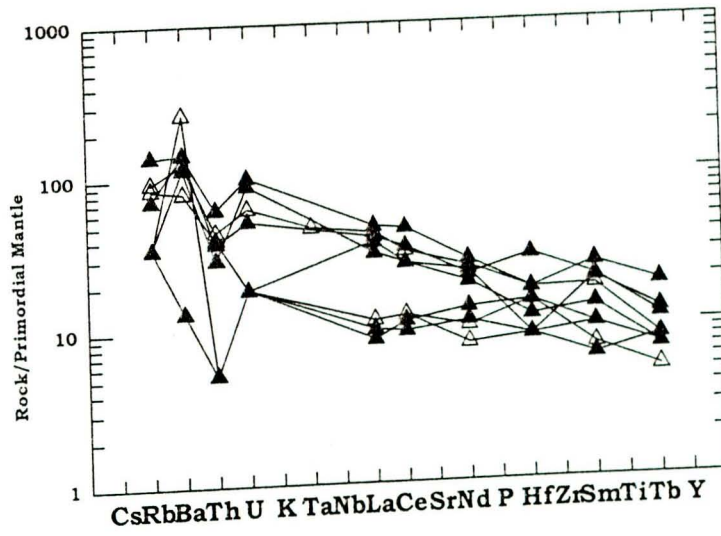
Fig. 5. 2. REE patterns for the metamorphic rocks at different Sc - Values



(a) Sc = 0 - 9 ppm



(b) Sc = 10 - 19 ppm



(c) Sc > 20 ppm

Fig. 5. 3. Incompatible element patterns for the metamorphic rocks at different Sc values

5. 2. 3. INFERENCES ON THE NATURE OF THE PROTOLITHS

Field investigations during the present work as well as previous studies have shown that the metamorphic rocks of the Negash area are mostly composed of metavolcanic rocks with subordinate sediments. The main objective is that of discriminating rocks of volcanic origin from that of sedimentary origin.

The texture of the rocks, the field relationships of the various rock types, and petrographic studies (see Chapter 3) are used to determine the origin. Relict igneous textures (e.g. relict porphyritic) which is observed in some samples confirms the magmatic nature of the rock. Moreover, trace element abundances and ratios as well as REE patterns have been used for further identification of the origin of the rocks.

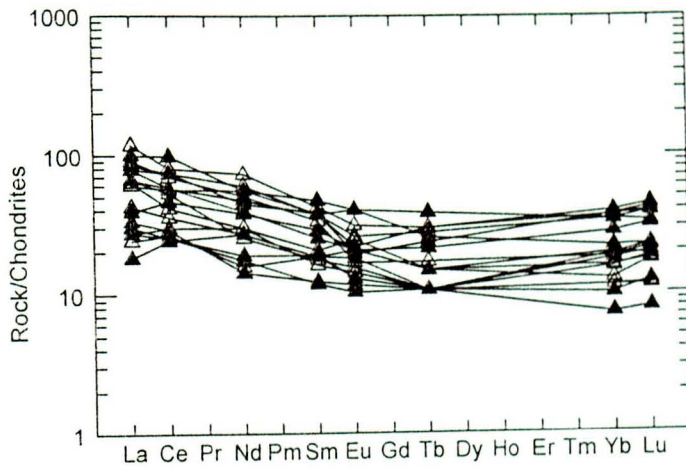
The geochemical criteria used to discriminate between metasediments and metavolcanics include the values of the FeO/CaO, concentration of Co, Cr and other trace elements, and the shape of REE patterns. For instance, FeO/CaO ratios around unity in conjunction with relatively high concentrations of Co and Cr have been taken as evidences for a mafic volcanic origin. High CaO/FeO, typical of calcite rich sediments, in conjunction with low ferromagnesian element contents have been used as evidences for a sedimentary origin.

Based on geochemical and textural criteria, the metamorphic rocks have been divided into metavolcanic and metasedimentary rocks, and have been plotted with different symbols in the following figures (Figure 5. 4 and 5.5). In some cases the criteria are not adequate to discriminate between the two.

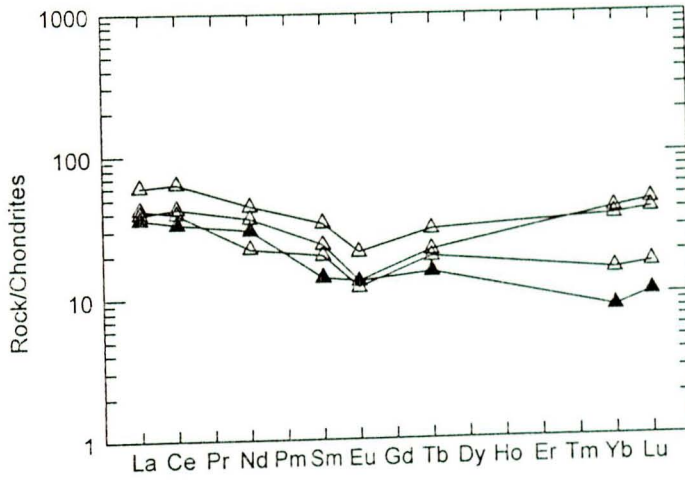
The metavolcanic rocks range in composition from mafic to felsic. The mafic rocks have high Sc, Cr, Co, Ni, FeO, CaO and some samples are enriched in Na₂O. Their REE patterns normalized to chondrites (Fig. 5.4 (a)) show either i) flat to slight positive fractionation with $Lu_N > La_N$, which is typical of tholeiitic basalts either from island arcs or oceanic environments. The high Na₂O of some samples is not in contradiction with this hypothesis, in as much as it may result from metasomatic processes; or ii) distinct negative fractionation ($La_N > Lu_N$), with fractionated LREE and flat or poorly fractionated HREE patterns, which are typical of calc alkaline andesites or basaltic andesites. The felsic metavolcanic rocks show slight negative Eu anomaly, enrichment of the HREE, and low Cr, Sc, Co, Ni, and FeO.

The metasediments generally have lower concentration of Sc, Cr, Co, Ni, FeO and higher Ba values than metavolcanics. Their REE patterns (Fig. 5.4. (b)) show large negative Eu anomalies, and generally lower amount of the LREE than that of the metavolcanic rocks.

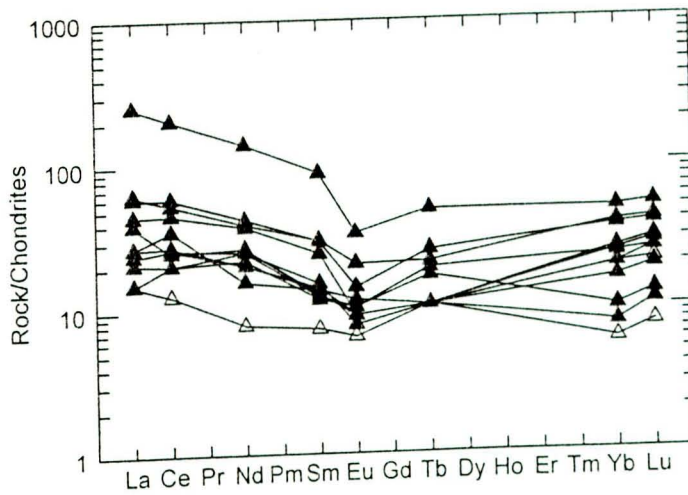
There are some samples which difficult to group either as metavolcanic rocks or metasediments. Most of these unclassified samples are highly silicified metamorphic rocks collected either close to the contact with Negash pluton or along the Suluh River. These rocks have been strongly affected either by metasomatism or contact metamorphism. They show variable features with respect to the general geochemical patterns that are typical of igneous and sedimentary rocks. Some samples (Fig. 5.4. (c)) show negative Eu anomalies and a LREE enrichment. These features could indicate a felsic volcanic protolith. However, these samples also have high Cr, Co and other ferromagnesian elements enrichment that conflicts with a felsic volcanic origin. Other samples have unusual REE patterns



(a) Metavolcanics



(b) Metasediments



(c) Unclassified

Fig. 5. 4. REE patterns for the three different groups of metamorphic rocks

(e.g. V shaped patterns) and are anomalously enriched in some of the elements (e.g. LREE) which makes inference of their original composition difficult.

Fig. 5.3. shows REE patterns for rock groups with different values of Sc. Fig 5.2(a) shows the REE patterns of rocks with Sc = 0 - 9 ppm, Fig 5.2 (b) for Sc = 10 - 19 ppm, and Fig 5.2 (c) for Sc > 20 ppm. The metavolcanic rock samples mostly have Sc values greater than 10 ppm, while the metasediments are generally depleted in Sc. The unclassified samples show variable Sc values. In the following discussion on the tectonic implications only samples for which the volcanic origin the protoliths has been positively constrained are used.

5. 2. 4. TECTONIC SETTING OF THE NEGASH METAVOLCANICS

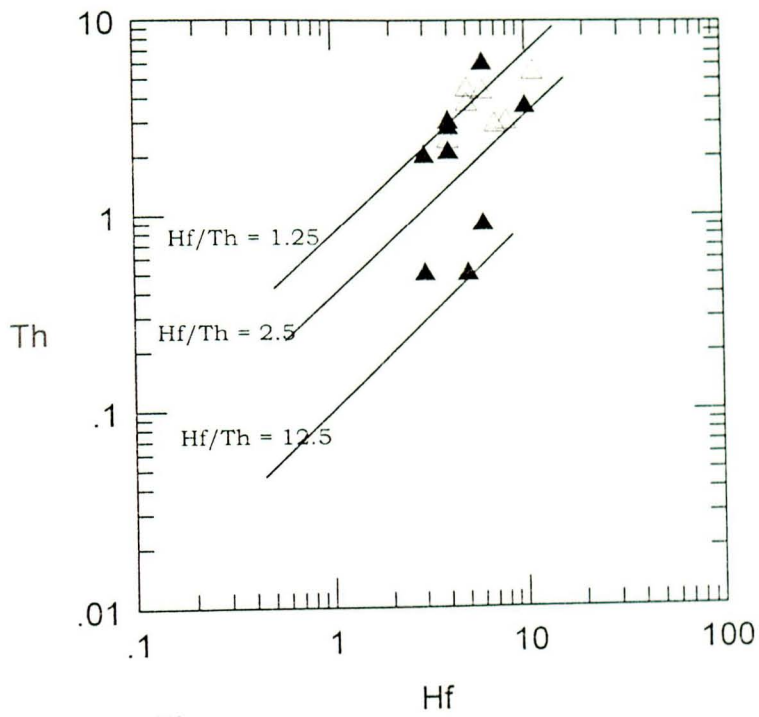
The discriminant diagrams of Wood et. al. (1979) (Fig. 5.5) are used for identifying the tectonic setting of the metavolcanic rocks. The elements used in the discriminant diagrams (Th, Hf, Ta and La) show relatively low mobility in low to medium grade regional metamorphism. Wood et. al. (1979) gave a detailed account on the suitability and limitations of these trace elements.

According to Wood et. al. (1979), Th versus Hf binary diagram is able to discriminate among basaltic rocks from different tectonic settings. On the Th versus Hf diagram (Fig. 5.5.(a)), the bulk of the metavolcanic rock samples plot in the same area of island arc tholeiites and calc - alkalic lavas from Japan (Wood et. al., 1979)

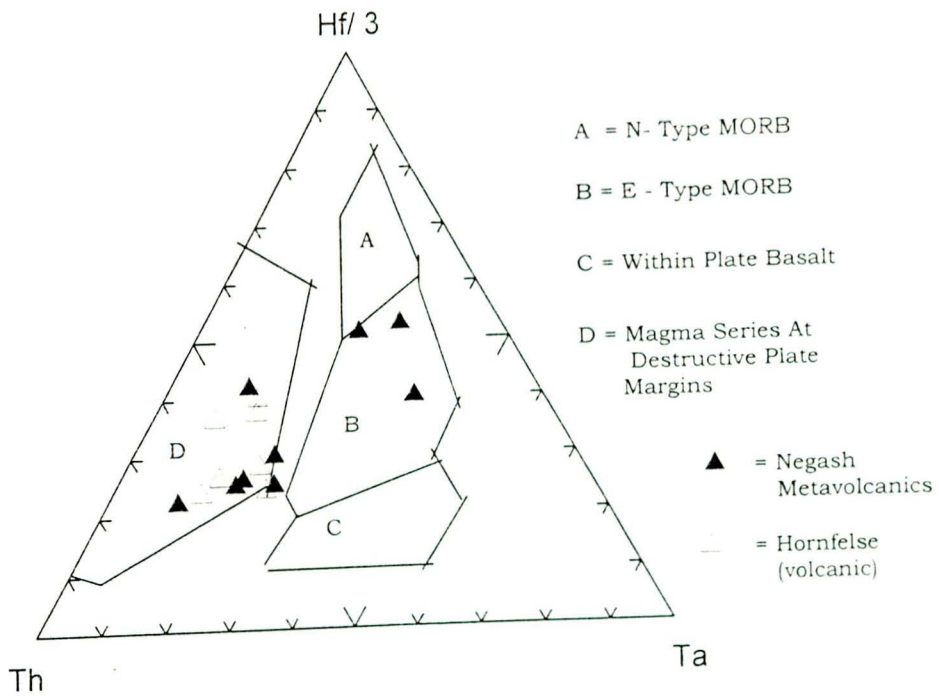
The Th - Ta and La - Ta diagrams are considered to be useful to separate basalt series from converging plate margins from that of MORB (Wood et. al. 1979). The bulk of the metavolcanic samples have Ta concentration below the detection limit, so it is not possible

to make a valid conclusion from these diagrams, but the rare samples which have Ta concentration above the detection limit fall within the island arc volcanic rocks of Wood et. a. (1979). The low Ta concentration also reinforces an arc setting for the studied metavolcanic rocks (e.g. Gill, 1981)

The biaxial discriminant diagrams have some limitations because only basaltic rocks can be successfully discriminated. But the metavolcanic rocks considered here include some intermediate and felsic compositions. Wood et. al. (1979) provided a triangular discriminant diagram based on Th - Hf - Ta, on which felsic volcanic rocks can be plotted along with the basaltic rocks, and constraining the tectonic setting of the rocks with variable degree of evolution is possible. The bulk of the metavolcanic samples plot in the field of the magmatic rocks from destructive plate margins, on the Th - Hf - Ta triangular diagram (Fig. 5.5 (b)) of Wood et. al. (1979) only a few samples (sample TG 47, 71, 98) plot on the E - type MORB basalts. It must be noted that these samples also have unfractionated REE patterns or have positively fractionated LREE. These features are typical of MORBs and may represent an evidence for their presence in association with arc type rocks. In conclusion, The metavolcanic rocks presumably formed in an intraoceanic volcanic arc type setting. In this context, the MORBs may represent the abyssal tholeiites that formed that formed at the base of the calc alkalic volcanic arc.



(A)



(B)

Fig. 5.5. Discriminant diagrams for tectonic setting (After Wood et. al., 1979). (a) Th vs. Hf Diagram, (b) Th - Hf - Ta Diagram.

CHAPTER 6**GEOCHEMISTRY OF THE GRANITOIDS****6. 1. GENERAL**

A total of 22 samples collected from various parts of the Negash pluton, as well as from the aplite, quartz porphyry dikes and pegmatitic dikes were analyzed for major and for some trace elements using X - ray fluorescence (XRF). In addition, 21 trace elements and 8 REE were determined by Instrumental Neutron Activation Analysis (INAA). Some elements (CaO, FeO, Na₂O, Rb, Sr, Ni, Cr, Ba, La, and Ce) have been analyzed using both XRF and INAA. The two methods show general agreement, eventhough the INAA data show consistently higher values than those from XRF. Moreover, there is poor correspondence for Ni and Ca, attributed to the analytical problems with INAA for these elements. The INAA data for these two elements has been disregarded.

XRF analyses were carried out at the Dipartimento di Scienze della Terra, University of Cosenza, Italy, using pressed powder pellets and using the method of Franzini et al. (1972). Precision for the XRF data is better than 5 % for Rb and Sr and better than 10 % for all other elements except Nb. Certified Reference Materials were used to check the accuracy of the data. Accuracy is good for all major and trace elements except for Nb. However, this element has poor accuracy for rocks whose Nb concentration is above 25 ppm, as in the case of the standard samples BR, NIMG, GSP1. This does not affect Nb concentration data lower than this value.

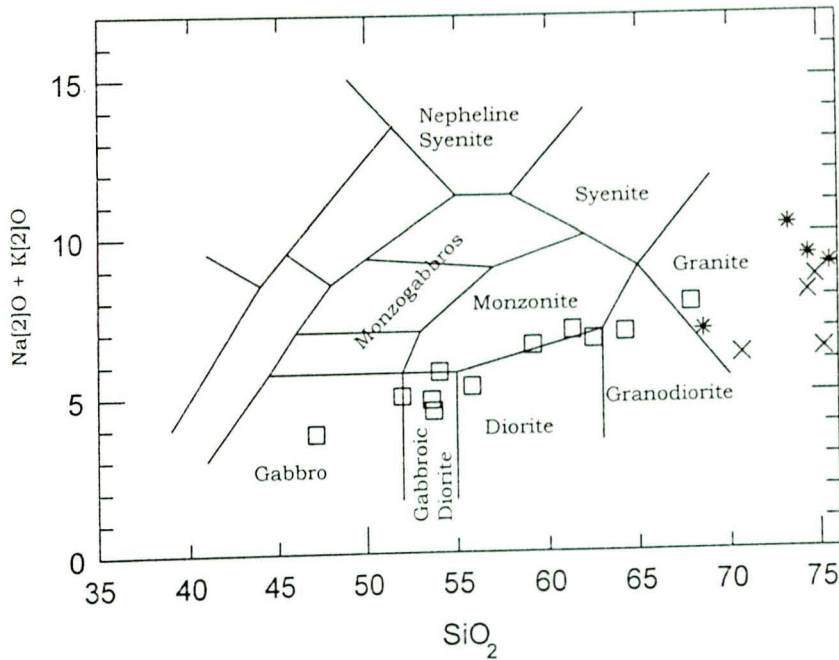
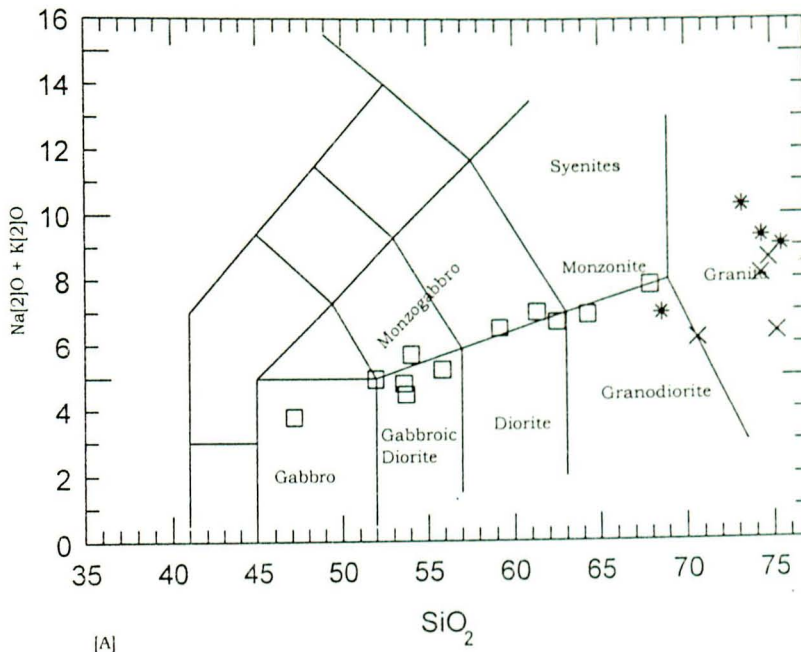
The data are treated in various ways using binary and triangular variation diagrams, petrologic (classification) diagrams, discriminant diagrams, normative mineralogical diagrams, REE patterns, and mantle-normalized diagrams. Based on those, the composition, the petrogenetic evolution, and the tectonic setting of the intrusion are discussed.

6. 2. COMPOSITION OF THE INTRUSIVE ROCKS

The petrographic studies made on samples collected from the intrusion revealed that the rocks range in composition from granite, through granodiorite, tonalite to diorite. The geochemical data is in agreement with the petrographic results

Classification Diagrams

All the samples analyzed are plotted on the diagrams of Le Bas et al. (1986) and Cox et al. (1979) which use the relationship of the Alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus silica (SiO_2) for classification purposes. The data show a fairly good correspondence on both diagrams (Fig. 6.1.(a) and (b)). The pegmatites, aplites, and granitic dikes plot in the granite field on both diagrams. The quartz porphyry dike falls in the granite field of Cox et. al. (1979) and in the granodiorite field of Le Bas et. al. (1986). The rocks classified as granodiorites on the basis of the modal mineralogy (Streckeisen, 1979) plot in the granodiorite field of Le Bas et. al.(1986) but in the granite field (close to the boundary line to the granodiorites) of Cox et. al (1979). The tonalites all fall in the monzonite field of both Le Bas and Cox diagrams. All the rocks classified as diorites on the basis of petrography, plot in the fields of diorites and gabbroic diorites of the chemical classification diagrams, except for a single sample which



□ = Intrusive rocks * = K - Rich Dikes × = K - poor dikes

Fig. 6.1. Classification Diagrams,
 [A] after LeBas et. al. (19 84),
 [B] after Cox et. al (1979)

fall in the gabbro field.

Based on the petrographic and geochemical studies, the pluton is composed of granodiorite, monzonite, diorite, and gabbroic diorite and is cut by numerous granitic, aplitic and pegmatitic dikes. Field evidence indicates that the rocks of mafic-intermediate composition, i.e. diorites, tonalites, and granodiorites are the dominant types. Granites are subordinate and occur mostly as hypabyssal bodies. Aplites and especially pegmatites are minor.

All the samples lie in the subalkaline field of the alkalis versus silica variation diagram (Fig. 6.2.) indicating that the whole intrusive rocks have subalkaline nature. K_2O versus SiO_2 diagram (Peccerillo and Taylor, 1976) (Fig. 6. 3) indicates that the bulk of the investigated intrusives represent a high - K calc alkaline suite. However, a group of hypabyssal rocks represented by aplites and pegmatites show low - K contents. Other dikes, i.e. quartz porphyry and granitic dikes, plot on the same trend as the intrusive rocks and possibly represent the most evolved rocks of the intrusive suite.

Normative Mineralogy Diagrams

The CIPW normative mineralogical composition of the analyzed samples have been calculated. All the samples are oversaturated in silica and contain significant to high amounts of normative quartz. The normative mineralogy has been used to classify the analyzed rocks in the Streckeisen (1975) classification diagram (Fig. 6. 4). Since little or no pure albite has been observed optically in most of the analyzed rocks, except pegmatite TG 51, all the normative albite was added to normative anorthite to form plagioclase. Accordingly, only normative orthoclase has been plotted on the alkali feldspar apex. The diagram shows that

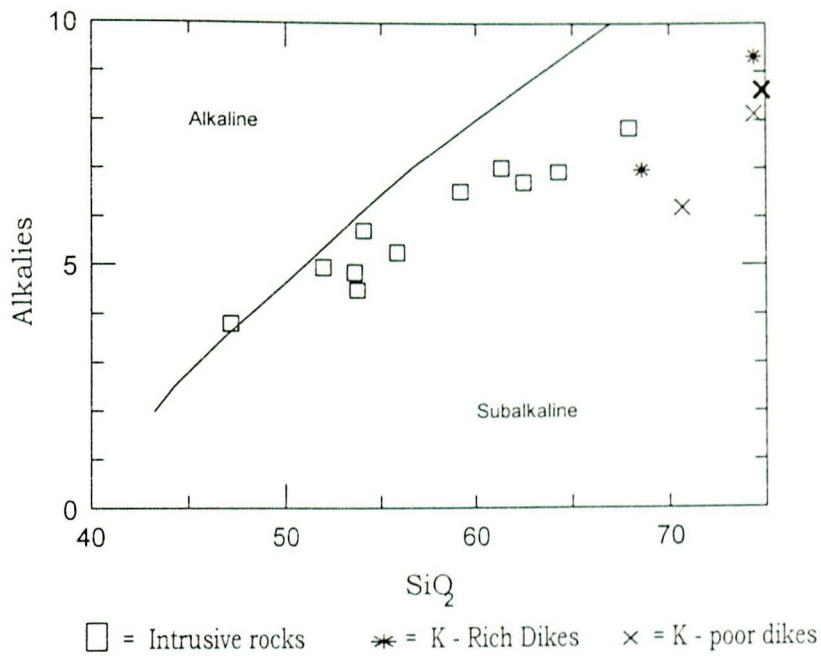


Fig. 6. 2. Silica vs. Alkali Diagram

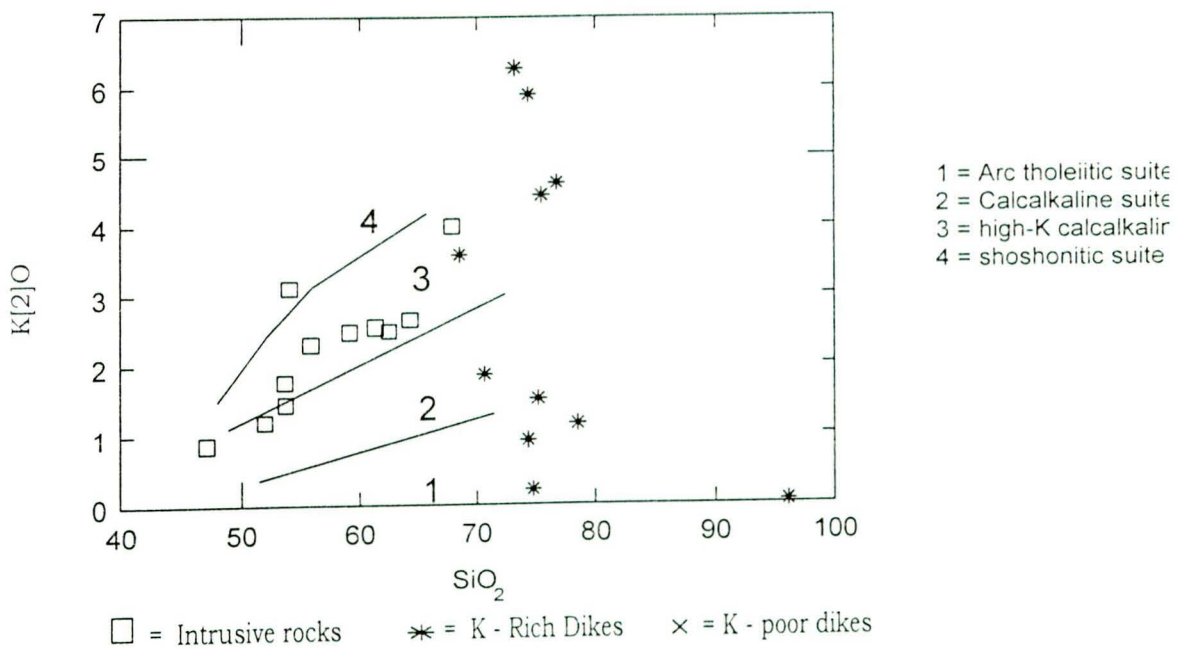
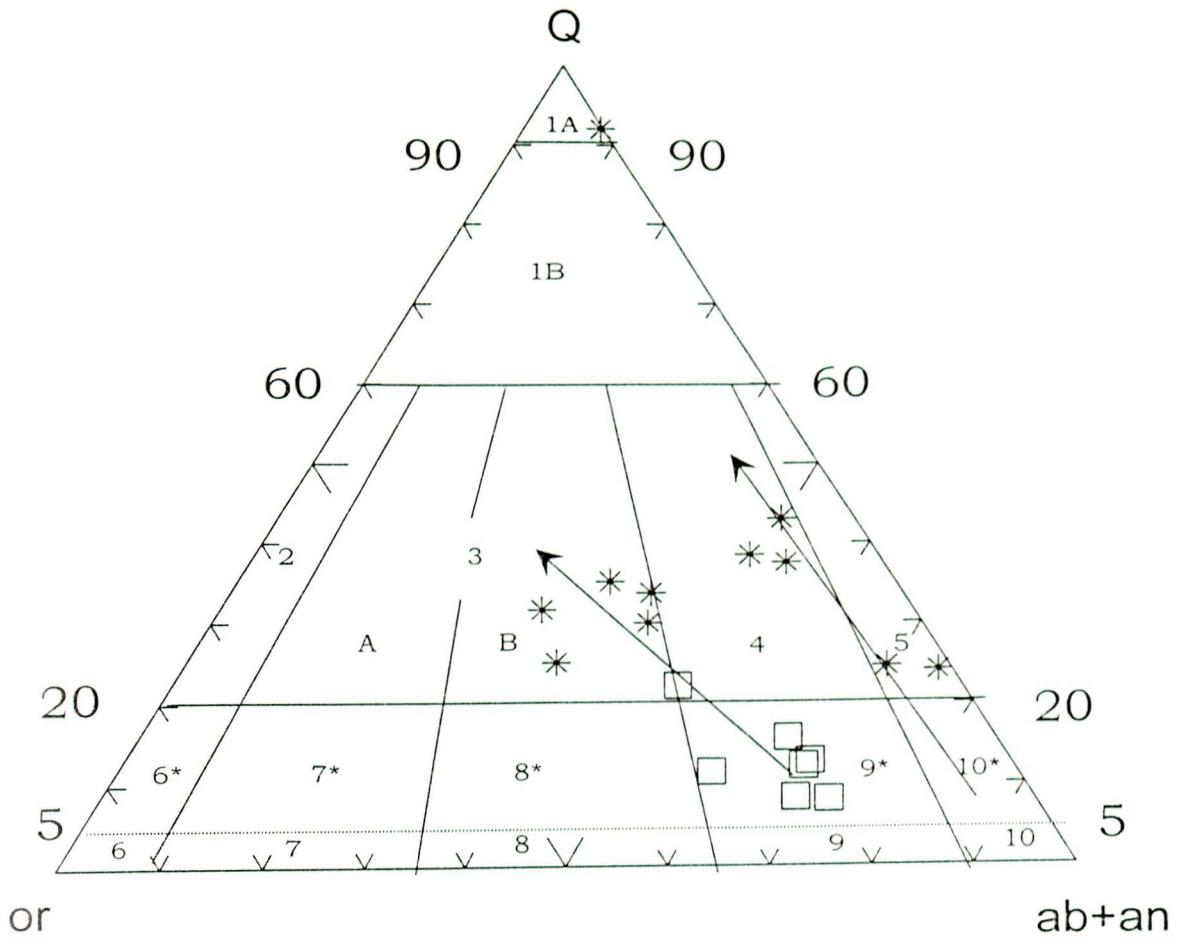


Fig. 6. 3. K[2]O vs. SiO[2] Classification Diagram
(After Peccerillo & Taylor, 1976) for the Negash granitoid rocks.



□ = INTRUSIVES

* = DIKES

1A = QUARTZOLITE

1B = QUARTZ -RICH GRANITOIDS

2 = ALKALI - FELDSPAR GRANITE

3 = GRANITE

4 = GRANODIORITE

5 = TONALITE

6* = QUARTZ ALKALI
FELDSPAR SYENITE

7* = QUARTZ SYENITE

8* = QUARTZ MONZONITE

9* = QUARTZ MONZODIORITE/
QUARTZ MONZOGABBRO

10* = QUARTZ DIORITE/
QUARTZ GABBRO

6 = ALKALI FELDSPAR
SYENITE

7 = SYENITE

8 = MONZONITE

9 = MONZODIORITE/
MONZOGABBRO

10 = DIORITE/ GABBRO/
ANORTHOSITE

Fig. 6. 4. Streckeisen Classification Diagram for Intrusive Rocks (After Streckeisen, 1979). The Negash Granitoid rocks plot in two different fields as shown by the arrows.

the plutonic rocks and the quartz porphyry and granite dikes define a trend ranging from quartz-monzodiorite to granite. Instead, the aplites and pegmatite plot within the tonalite to quartz-rich compositional fields.

Major Element vs. SiO₂ Variation Diagrams

The Harker diagrams for the major and minor elements are shown in Fig. 6. 5. Among the major and minor elements TiO₂, P₂O₅, Fe₂O₃, FeO, MnO, CaO, show very distinct and strong negative correlation, while Na₂O and K₂O show a positive correlation. However, the aplite and pegmatite rocks display a negative trend of SiO₂ versus K₂O. Two aplite samples also display anomalous enrichment in Na₂O. Al₂O₃ shows an increase and then a decrease with increasing silica content. The dioritic - monzonitic rocks show high concentrations of TiO₂, P₂O₅, Fe₂O₃, FeO, MnO and CaO than the granodioritic - granitic rocks which are more enriched in alkalis.

Trace Element vs. SiO₂ Variation Diagrams

The variation diagrams of the trace elements versus SiO₂ (Fig. 6.6) give consistent results that mimic major and minor element patterns. Among the trace elements, the ferromagnesian elements : V, Cr, Ni, Sc, Co, and Zn show strong negative correlation with silica. Y and, to a lower degree, Sr also decrease with increasing silica contents. Zirconium

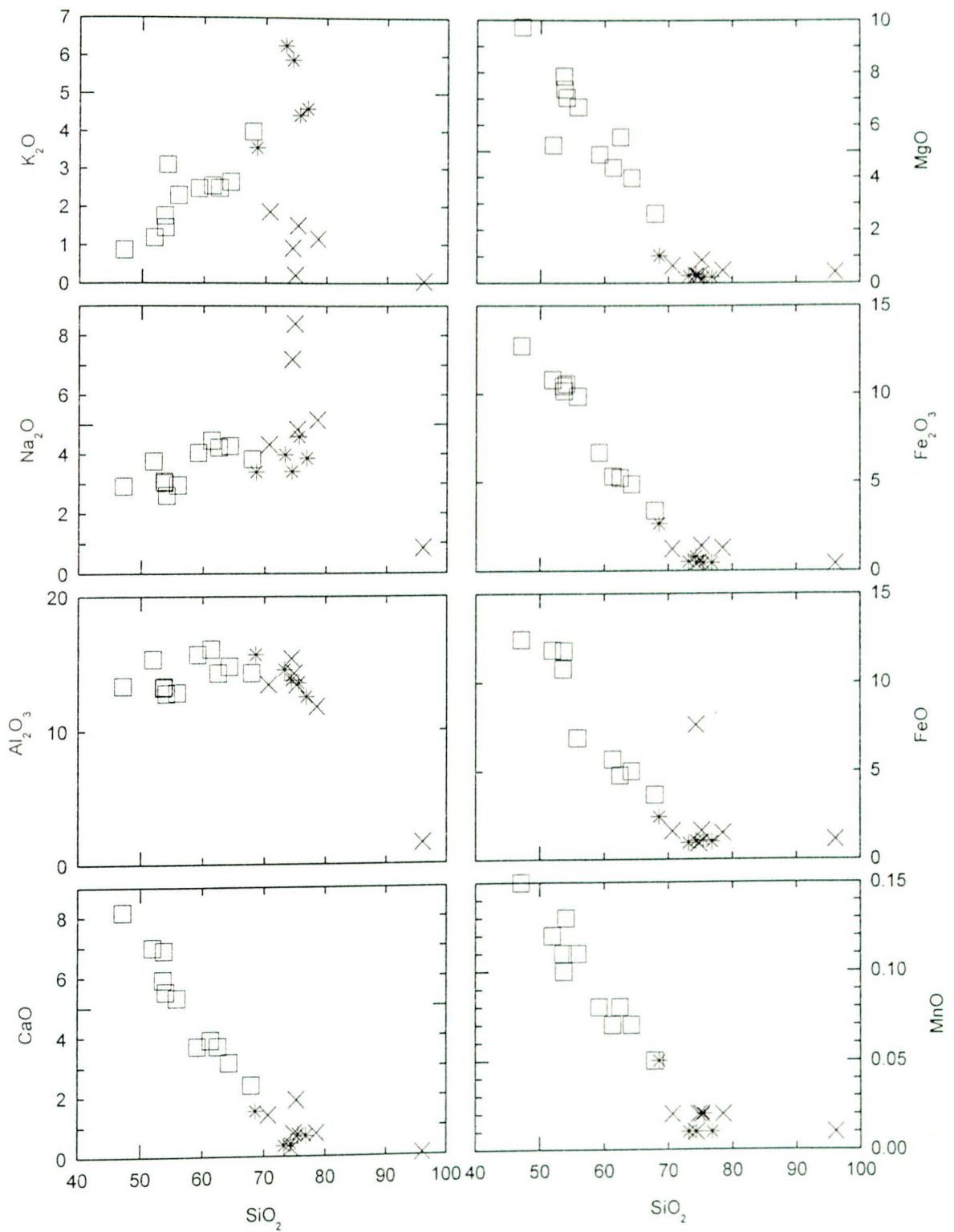


Fig. 6. 5 . SiO_2 variation diagrams for the major elements, rocks from the Negash granitoid.

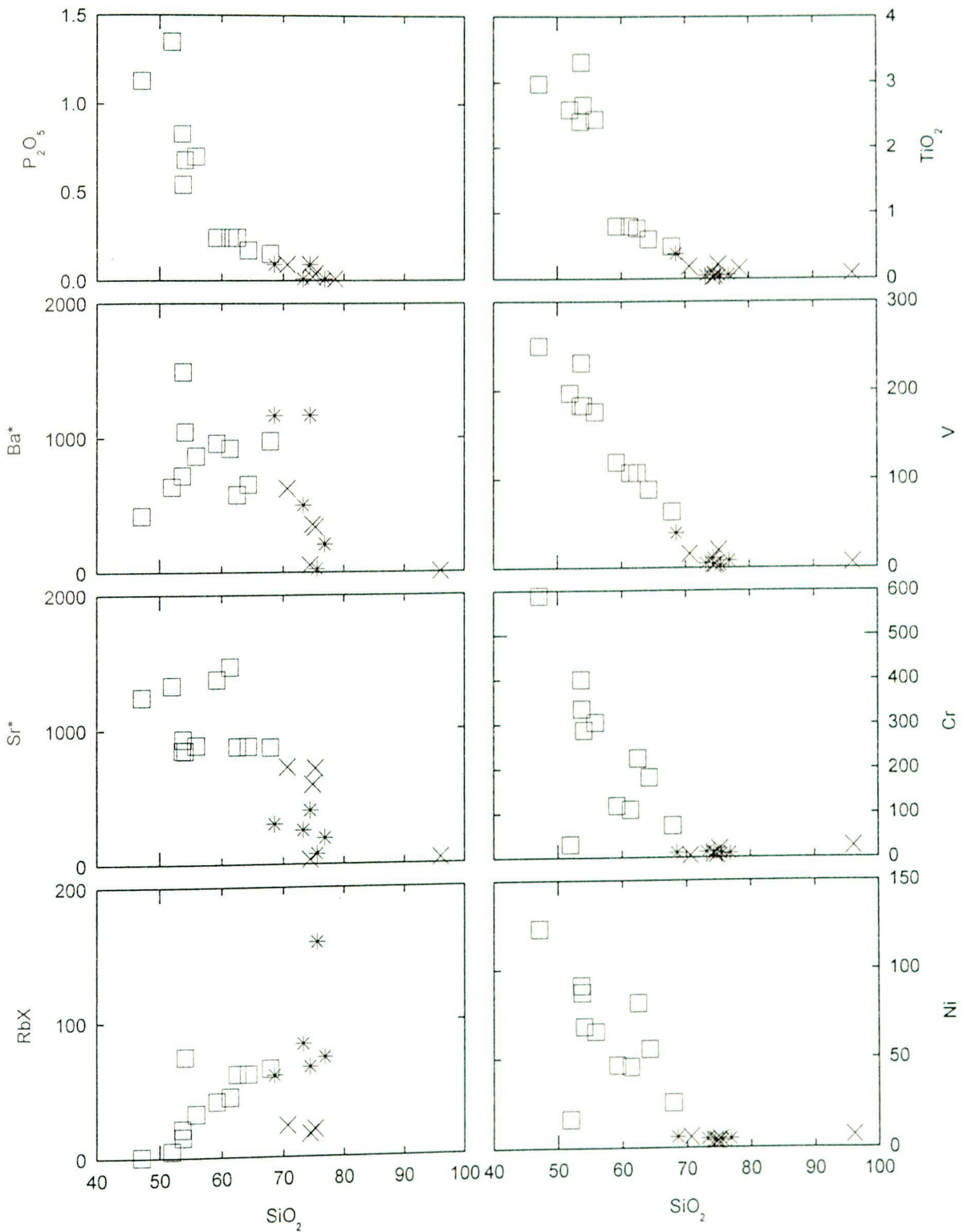


Fig. 6. 6 . SiO_2 variation diagrams for trace elements, rocks from the Negash granitoid.

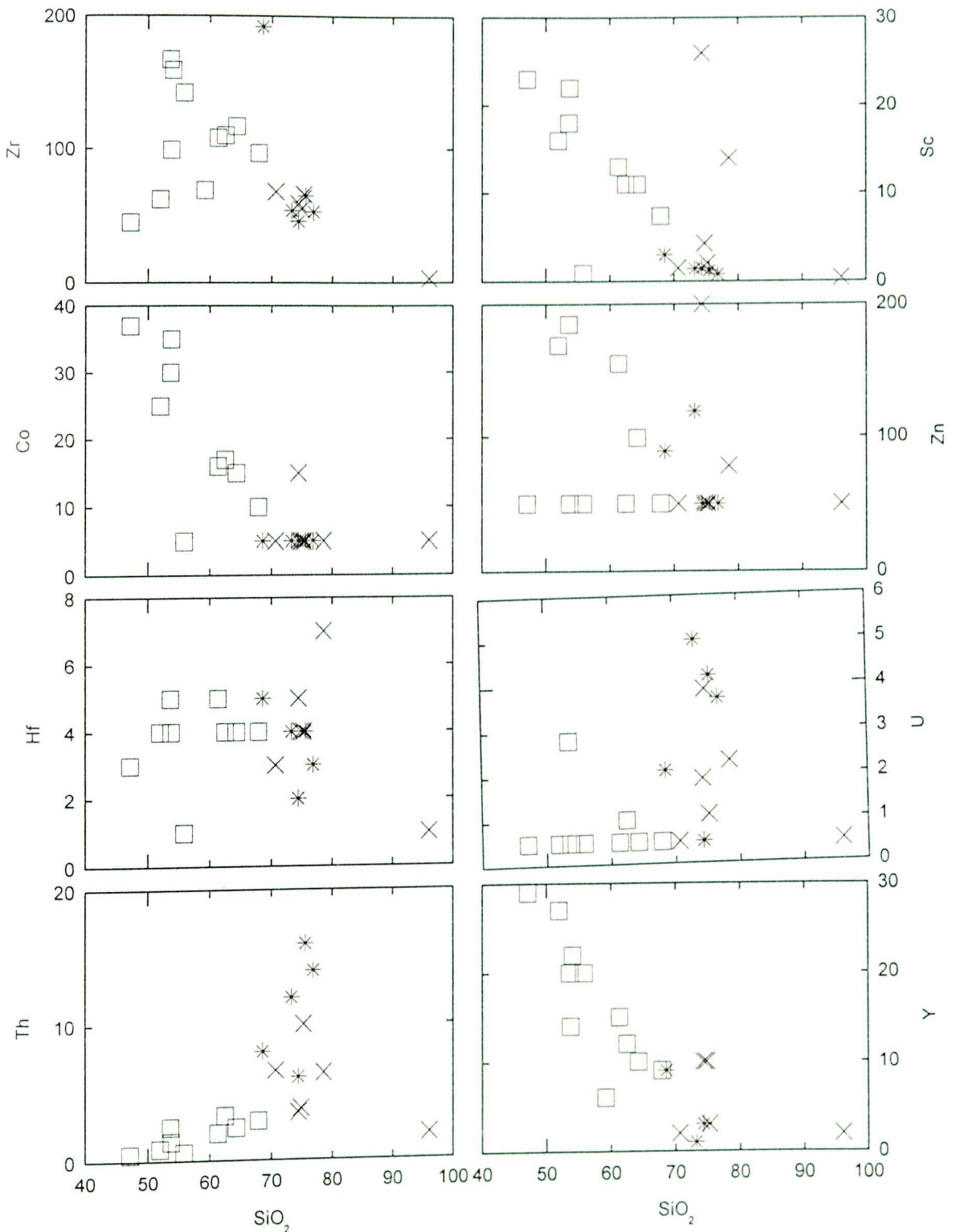


Fig. 6. 6 . SiO₂ variation diagrams for trace elements, rocks from the Negash granitoid.

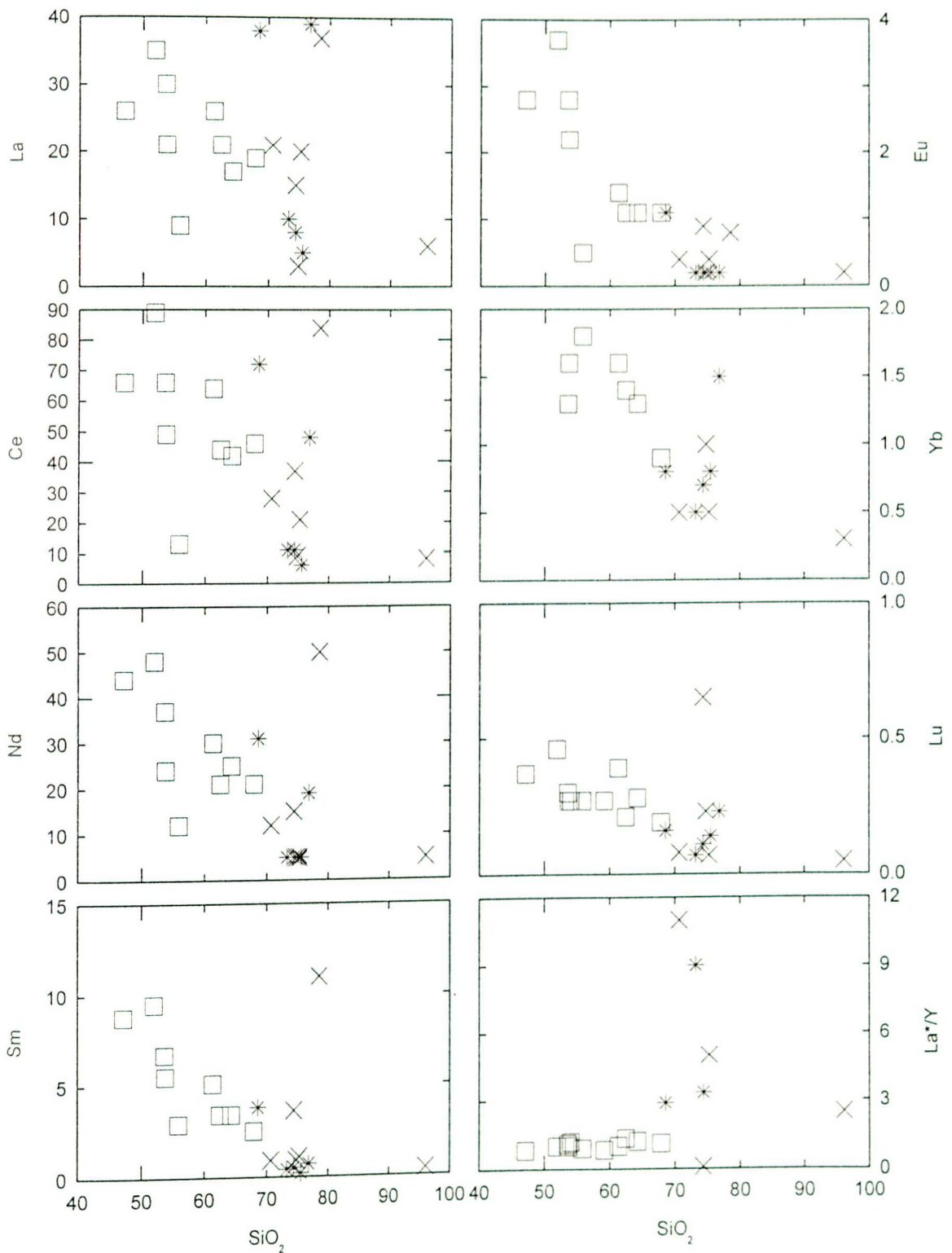


Fig. 6. 7 . SiO₂ variation diagrams for REEs rocks from the Negash granitoid.

increases in the mafic samples to decrease in the felsic rocks. Some samples display high Zr contents with respect to other rocks with the same silica contents. Thorium and Rb show positive correlation with SiO_2 with a strong increase in the most fractionated intrusives. Tantalum, Sn, Sb, Au, As and Mo have concentrations below the detection limits. All the REE show negative correlation with SiO_2 ; however, there is a large scatter of data points in the most felsic rocks. La/Y ratios show an overall increase with SiO_2 , reaching very high values in some of the most acidic rocks. However some dikes have low La/Y ratios (Fig. 6.7).

Triangular Variation Diagrams

The AFM and ACF diagrams are shown in Figures 6.8 and 6.9. The samples plot near to the alkalis corner and there is a clear trend of fractionation from the dioritic rocks which are equally enriched in Fe_2O_3 and MgO or Fe_2O_3 and CaO, to the granodioritic and granitic rocks which are enriched in alkalis. The bulk of the samples plot in the calc - alkaline compositional field with a few samples plotting in the tholeiitic field.

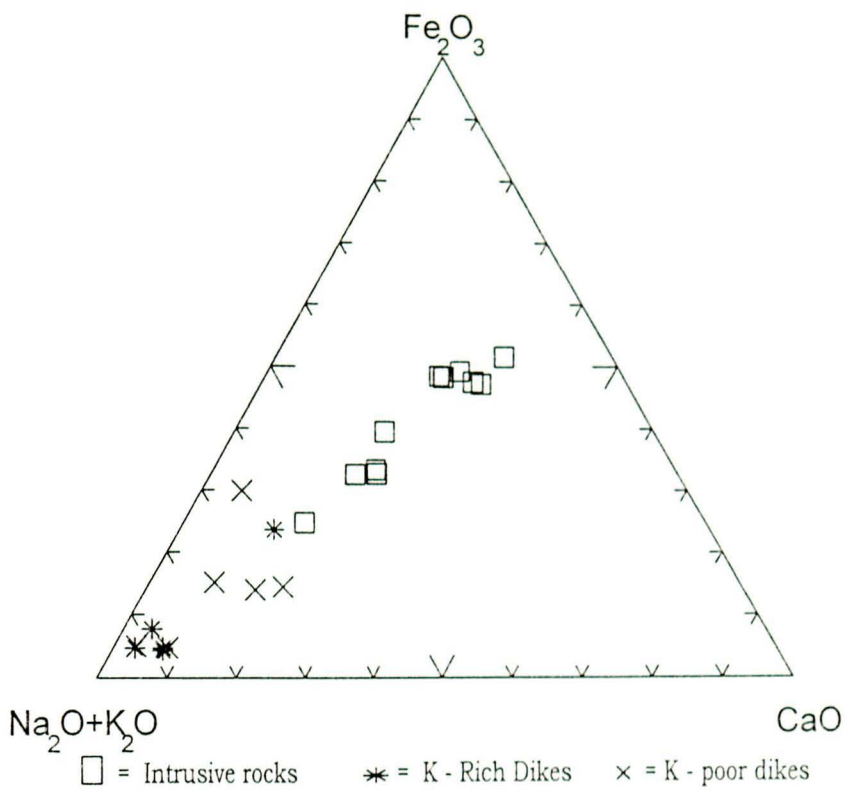


Fig. 6. 8. ACF diagram for rocks from the Negash granitoid

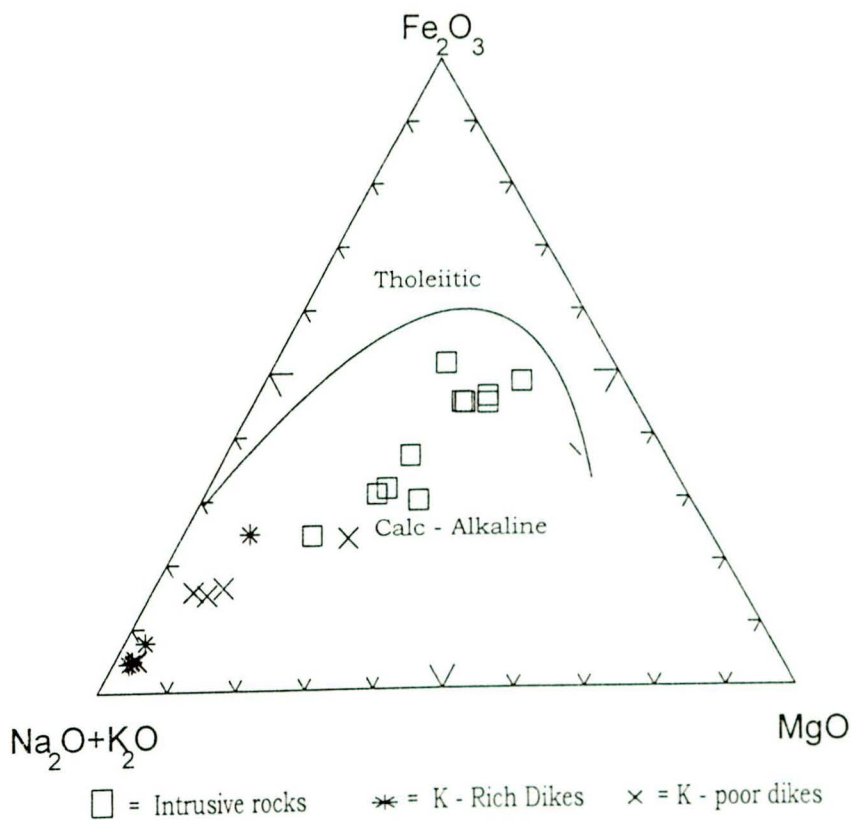


Fig. 6.9. AFM diagram for rocks from the Negash granitoid

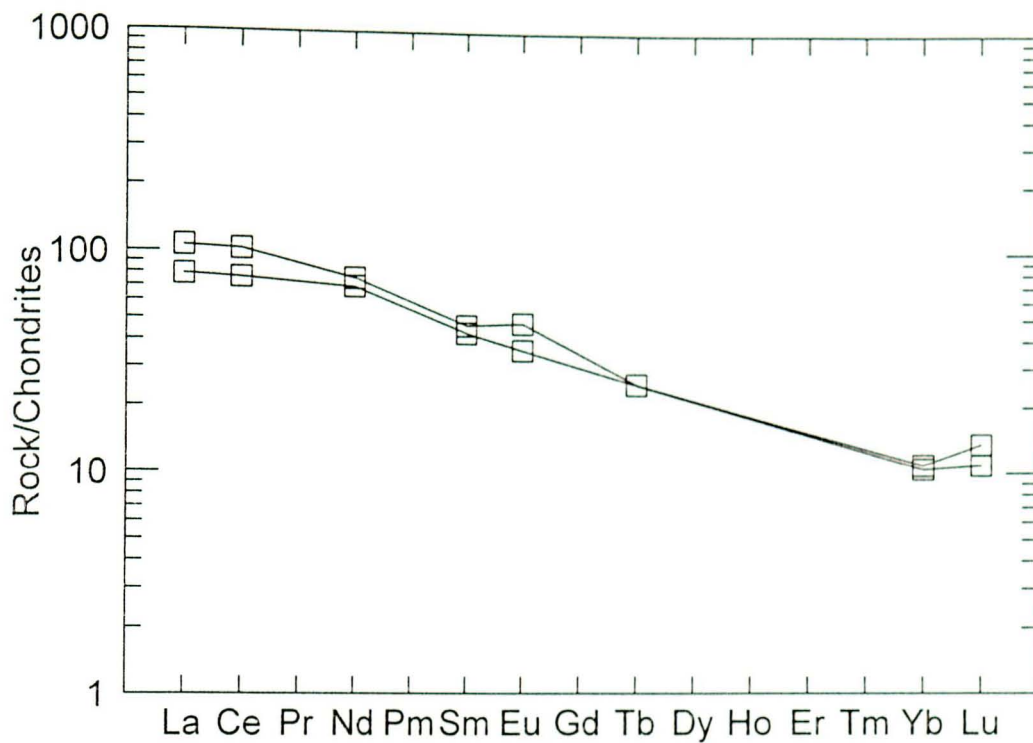
The REE patterns normalized to chondrites (Fig. 6.10) show variable shapes. The mafic rocks have fractionated patterns for both LREE and HREE. A small positive Eu anomaly is present in some samples. The intermediate rocks show similar patterns as the mafic rocks, although the absolute abundance of REE becomes slightly lower. The felsic rocks display very variable patterns. Some samples have smooth patterns and resemble the intermediate and mafic intrusives while others display more complex patterns with negative Eu anomalies and in some cases, of Ce and, oddly enough, Sm. Strong enrichment in HREE is also shown by some samples.

6. 3. TECTONIC SETTING OF THE NEGASH PLUTON

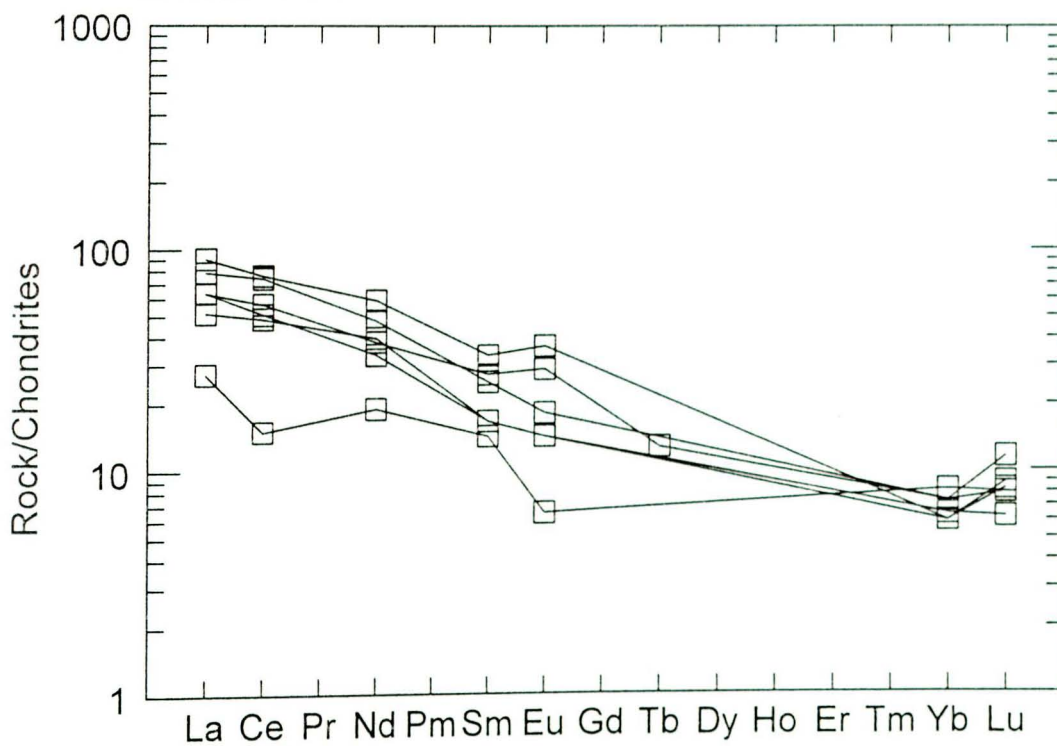
The tectonic setting of granitoids can be recognized by the trace element - SiO_2 variation diagrams and trace element discrimination diagrams of Pearce et al. (1984). However, there are some problems with trace element discrimination diagrams for granitoid rocks, as it will be discussed later.

Trace Element - SiO_2 Variation Diagrams

SiO_2 variation diagrams for Rb, Y, Ta, and Tb have proved to be very good discriminants of granitoids from various tectonic settings (Pearce et al., 1984). All the analyzed samples for the Negash intrusion are plotted in those variation diagrams (Fig. 6 . 11) and all the diagrams invariably indicate the same type of tectonic setting for all samples.



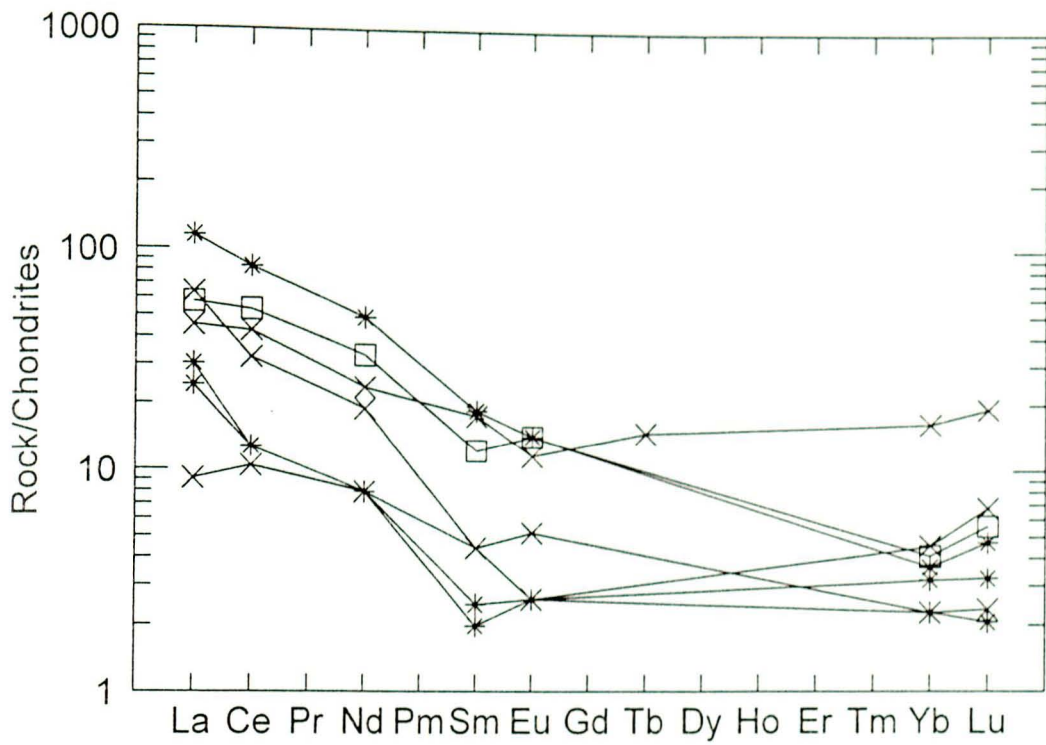
(a) SiO₂ < 52 %



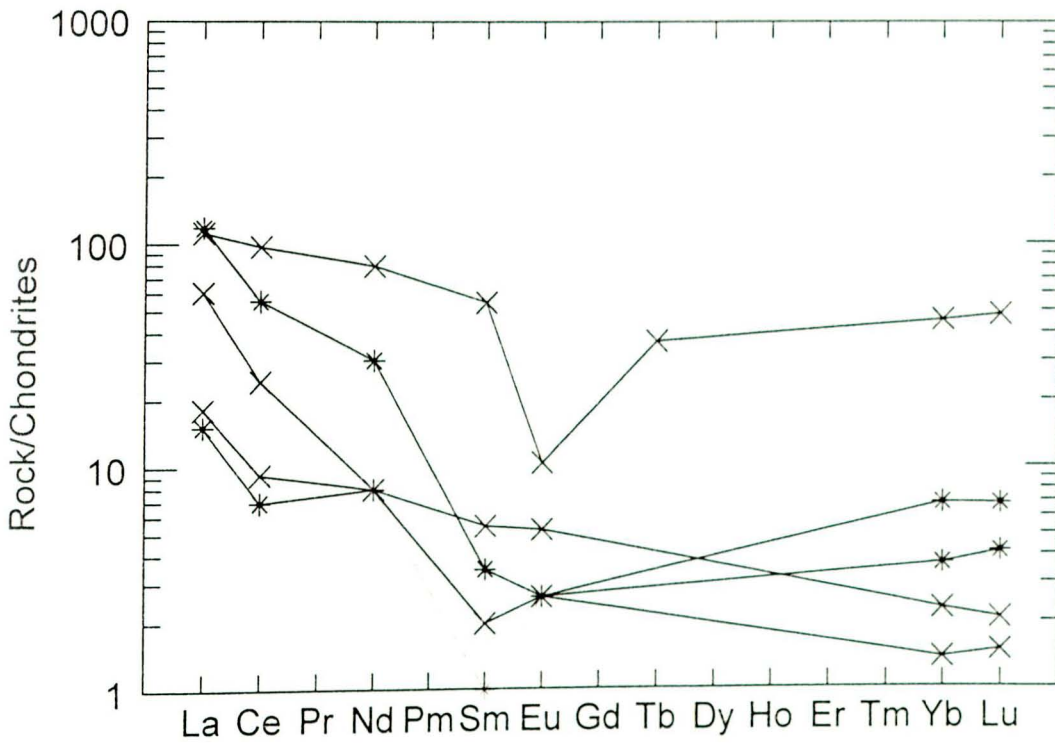
(b) SiO₂ = 52.01 - 65 %

□ = Intrusive rocks * = K - Rich Dikes x = K - poor dikes

Fig. 6. 10. REE patterns at different silica contents, for rocks from the Negash granitoid



(c) SiO₂ = 65.01 - 75 %



(d) SiO₂ > 75.01 %

□ = Intrusive rocks * = K-Rich Dikes x = K-poor dikes

Fig. 6. 10. Continued

In the Y - SiO₂ and Nb - SiO₂ variation diagrams all the samples plot in the field of VAG (volcanic arc granites) - COLG (collision granites); in the Tb - SiO₂ and Ta - SiO₂ diagrams they plot in the VAG field.

Rb - Y - Nb and Rb - Yb - Ta Discrimination Diagrams

Variation and abundance of these elements are proved to be very reliable in the discrimination of tectonic setting of granitoids. All the analyzed samples from the Negash pluton plot at the top of the VAG field in Rb vs. (Y + Nb) and Rb vs. (Ta + Yb) variation diagrams and in the field of VAG + syn COLG field in the Nb vs. Y discriminant diagram (Fig. 6. 12). These plots favour a volcanic arc tectonic setting for the Negash pluton.

The tectonic setting of the metamorphic rocks intruded by the Negash pluton indicate a volcanic arc tectonic setting of subduction nature, which favours the conclusion that the granitoid body has a volcanic arc setting.

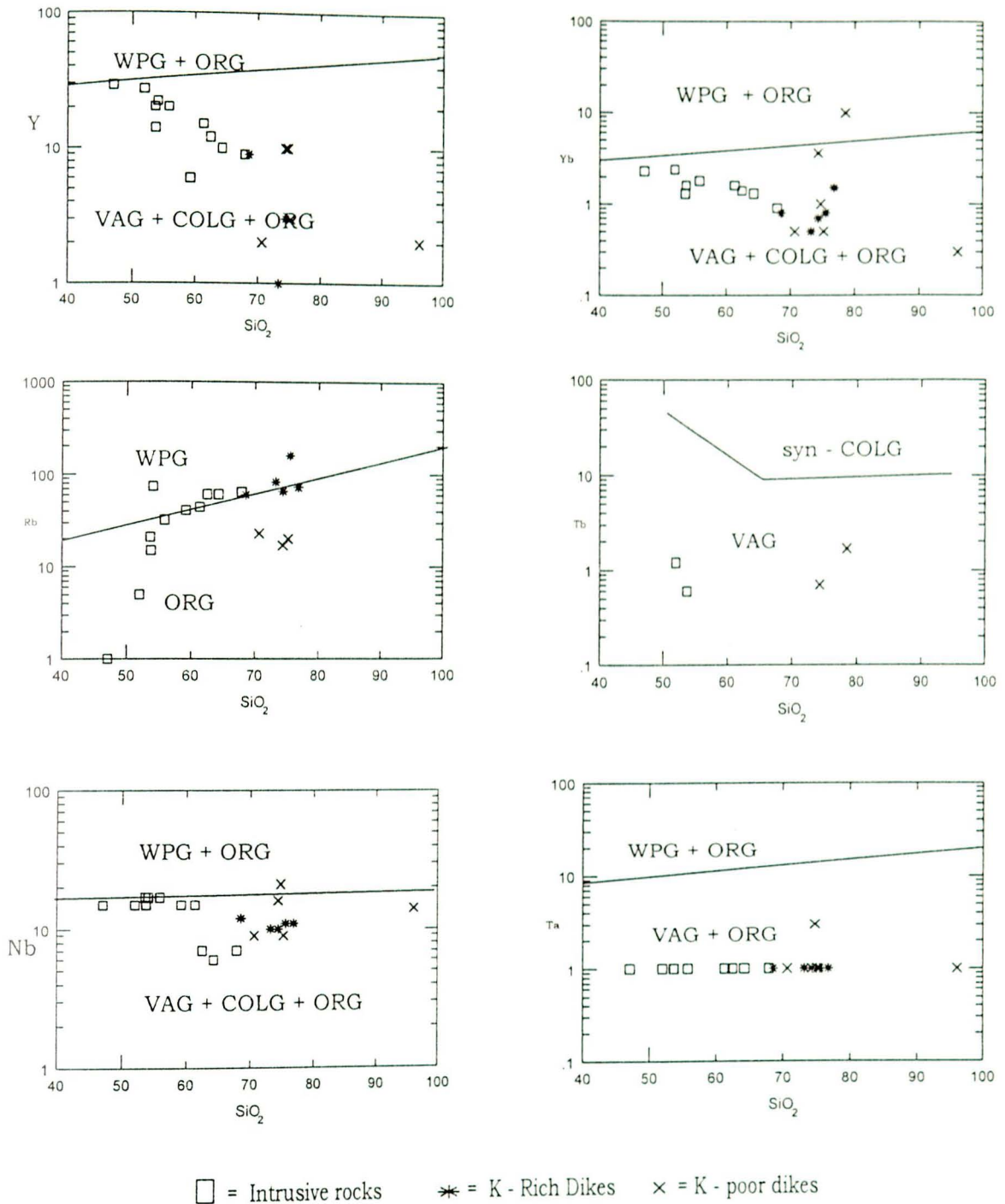


Fig. 6. 11. SiO₂ variation diagrams for Rb, Y, Yb, Ta and Tb, for the rocks from Negash granitoid

WPG = Within Plate Granites VAG = Volcanic Arc Granites
 COLG = Collision Granites ORG = Oceanic Ridge Granites

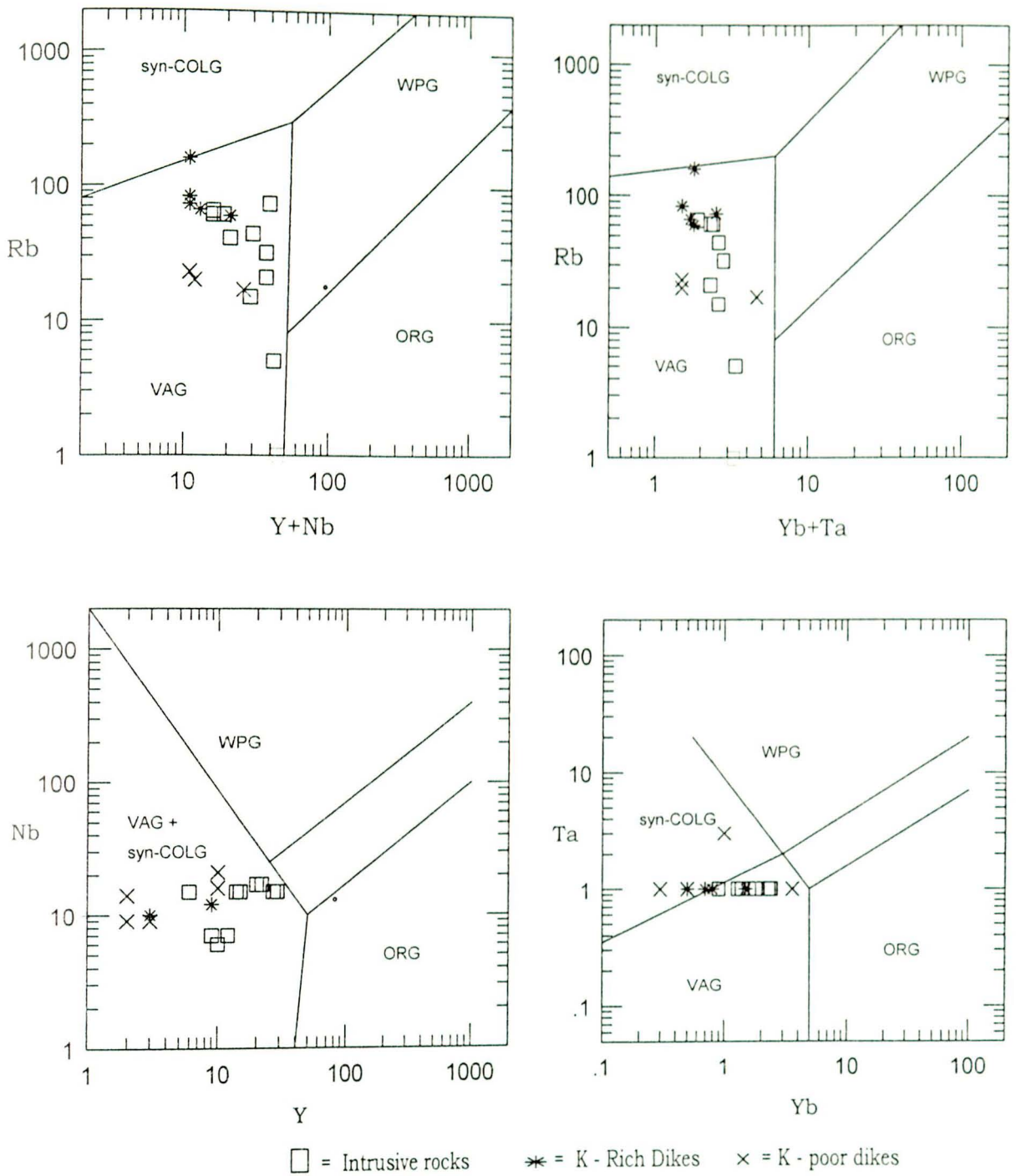


Fig. 6. 12. Trace Element discriminant diagrams (After Pearce et. al., 1984) for the rocks from the Negash granitoid.

6. 4. PETROGENESIS

The data obtained in the present work allow to draw a model for the petrogenesis of the intrusive rocks under consideration. This has a twofold objective in understanding the genesis and the evolutionary history of intrusive magmas as well as of shedding light on the possible relationship between magmatic processes and the mineralization events which have been observed in the country rocks (see Appendix A).

In discussing the petrogenesis of the Negash pluton both field relationship and geochemical data must be taken into consideration. Field work has shown that the granitoid body consist of large amounts of mafic to intermediate rocks with minor abundance of felsic rocks. The mafic to intermediate rocks contain abundant hornblende and biotite with minor pyroxene. The volume proportion between mafic and felsic rocks should become even higher at depth. In fact, due to density differences and relative buoyancy, the silicic magma move upward and, that explains the abundance of felsic composition in the exposed part of the Negash pluton, and should not be representative of the whole plutonic mass.

Major and trace element variation diagrams have shown that most of the intrusive rocks define regular patterns which can be interpreted as liquid lines of descent. On the contrary, the felsic rocks show no patterns, with many samples plotting outside the trends defined by the bulk of the intrusive rocks.

These data suggest that the generation of Negash pluton was principally governed by evolutionary processes starting from parental mafic magmas. Fractional crystallization appears to have been the most important process during magmatic evolution. However, it

cannot be excluded that there was some assimilation of country rocks, even though isotopic investigations should be carried out to establish the role of this process.

The scattering of data on variation diagrams shown by the most felsic rocks does not fit the simple fractional crystallization model which can explain the bulk of the plutonic mass, and these rocks require some alternative explanation.

In the following paragraphs attempt will be done to discuss in a greater detail the genesis of the bulk of the plutonic mass in order to put quantitative constraints on the minerals involved in the fractionation, and eventually assimilation, and on the volumes of mafic magmas required to give the observed residual melts. Moreover, the possible mechanisms which generated the scattering in the elemental distribution of the most felsic rocks, will be discussed.

Geochemical Modeling

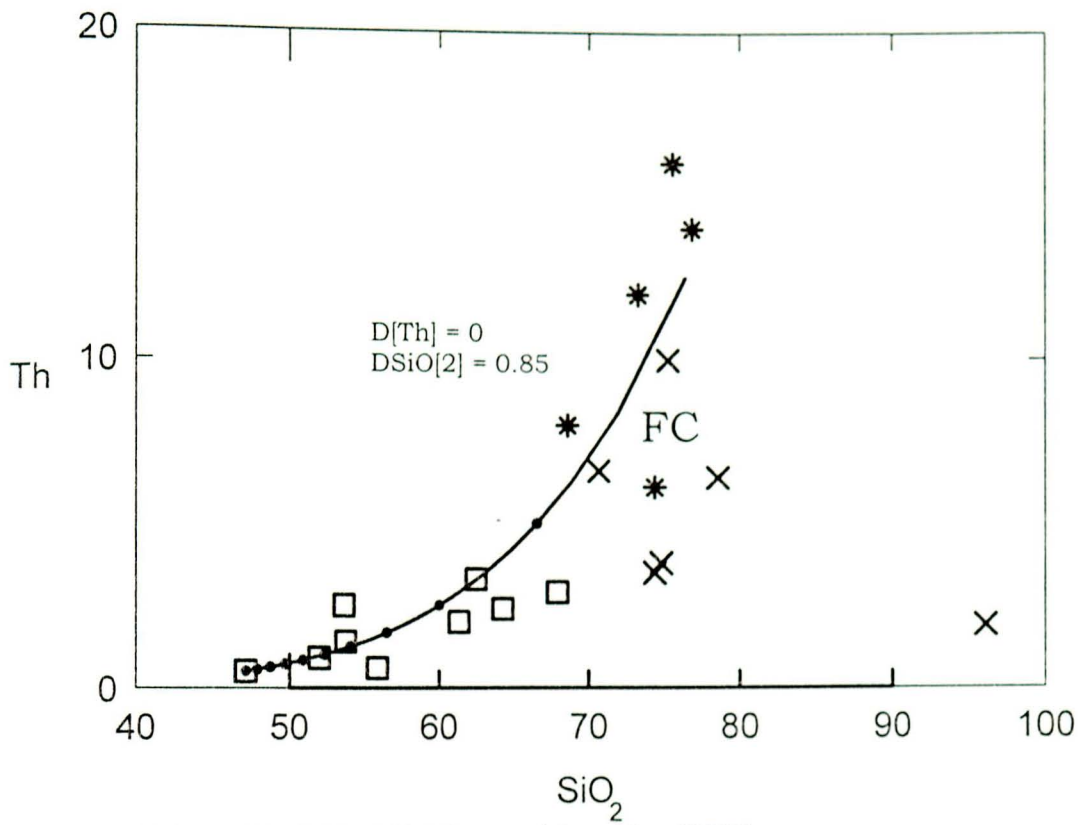
Quantitative modeling has been attempted in order to put constraints on the genesis of the Negash pluton. The results of these modeling are reported in Fig. 6.13, Fig. 6.14 Fig. 6. 15, Fig. 6.16 and Fig. 6.17. Values of bulk partition coefficients are given in the figures. Each dot along the lines represent 10 % fractionation.

Modeling based on Th versus silica (fig. 6. 13 (a)) indicates that the entire suite of the plutonic rocks, including some of the dikes, can be explained by extensive fractional crystallization starting from the most mafic magmas. A slightly incompatible behaviour should be assumed for silica, whereas Th should behave as a strongly incompatible element with $D_{s/l} = 0.05$. This requires that the mineral phases which separated during fractionation

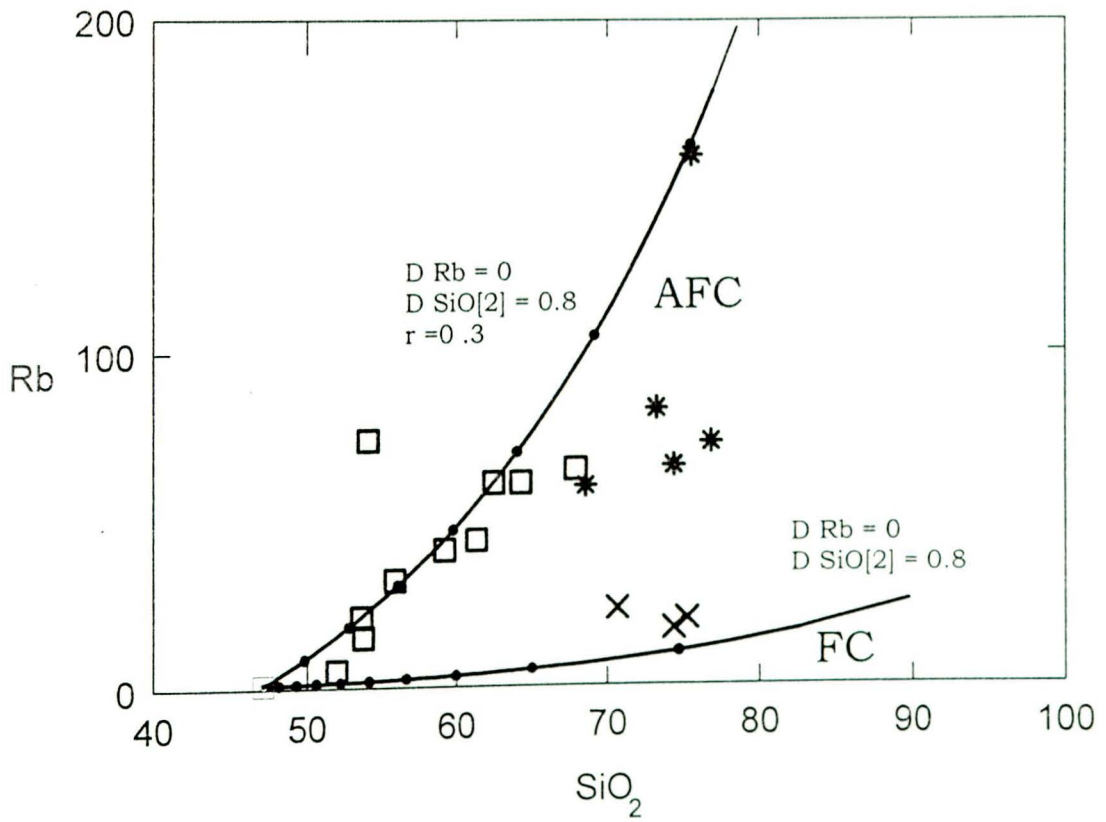
did not host Th in their lattice. This occurs in almost all the major rock forming minerals such as feldspar, amphibole and pyroxene.

Modeling of Rb variations (Fig. 6. 13 (b)) indicates that the observed increases in Rb cannot be accounted for by simple fractional crystallization, also if a $D = 0$ is assumed for Rb. In other words, there is an exceedingly high increase in Rb which is inconsistent with simple fractional crystallization. AFC (Assimilation plus Fractional Crystallization) modeling with assimilation of upper crustal material with a composition as that some of the analyzed metasediments can account for the anomalous increase in Rb observed in the intrusive sequence. Accordingly, Rb modeling suggests that AFC rather than simple FC may be a better model for the Negash intrusive suite. The AFC process could have given important effects only on some elements (e.g. Rb) and not on others (e.g. Th). The models based on Th and Rb are not contradictory. The strongly incompatible behaviour of Rb suggests that biotite, which is the only common rock forming mineral which hosts Rb, did not play an important role during evolution.

Variation of Y versus SiO₂ (Fig. 6. 14 (a)) for the intrusive suite indicates that Y behaved as a compatible element during evolution. Geochemical modeling suggests a $D_Y = 2$. Y can enter in the lattice of hornblende, but also in some accessory phases such as zircon and allanite. However, zircon does not appear to have separated until the intermediate stages of evolution (see next paragraph). This leads to the conclusion that hornblende was a major separating phase during the entire evolutionary history of the pluton. Gill (1981) gives $D_{s/l}$ of Y in hornblende around 2-3. The need of assuming a $D_Y = 2$ in the model implies that hornblende was by far the most important separating phase during AFC.



[a] Fractional crystallization model on Th - SiO_2



(b) FC and AFC model on Rb - SiO_2

Fig. 6.13. Geochemical Modeling on Th - SiO_2 and Rb - SiO_2 for the Negash granitoid

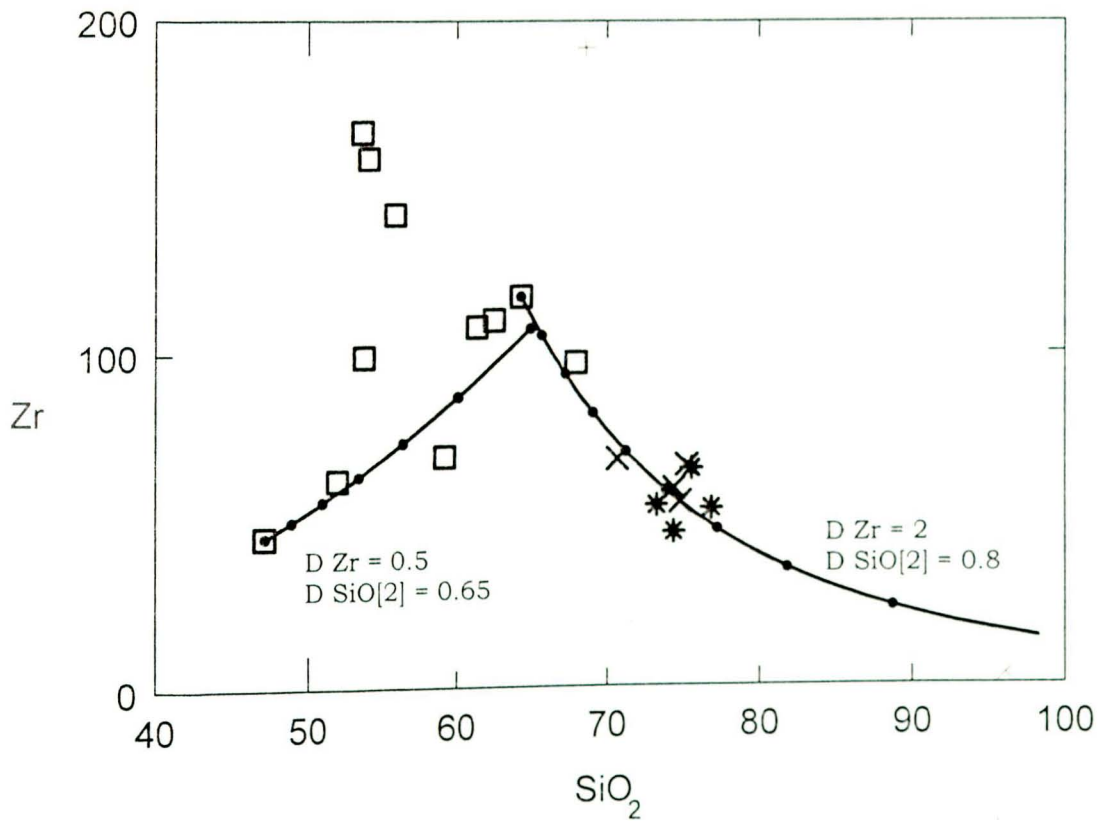
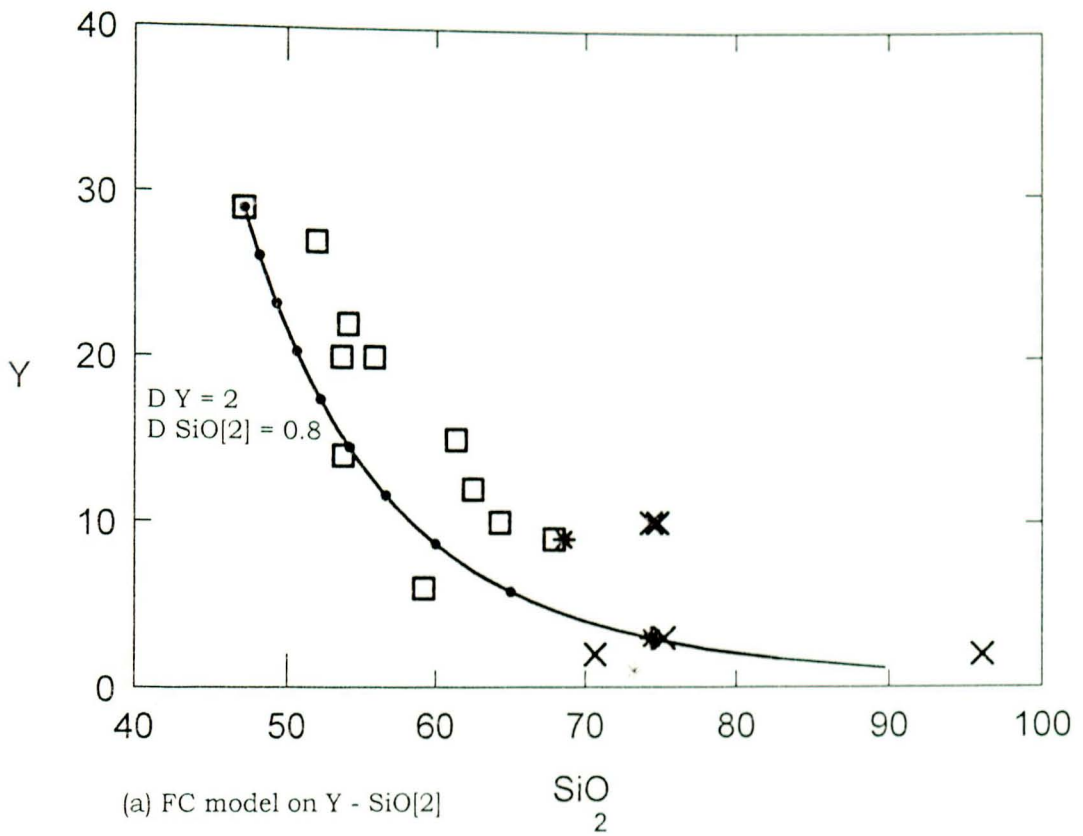


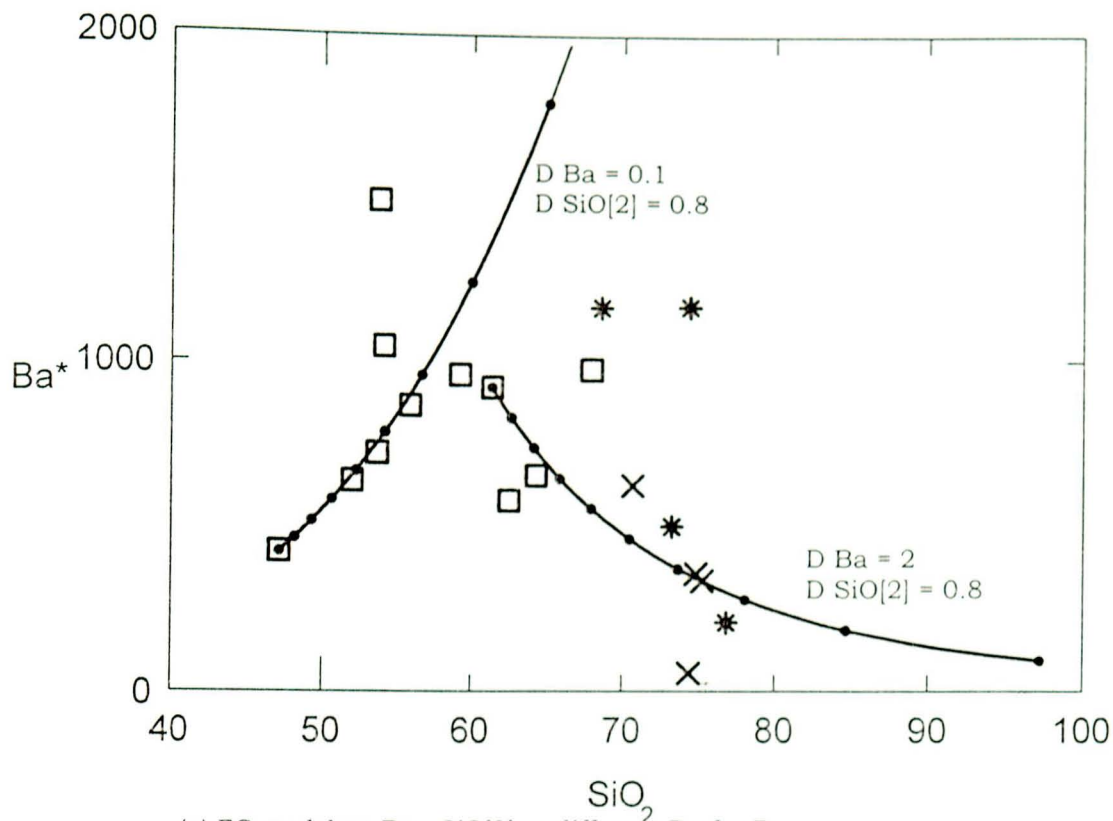
Fig. 6 .14. Geochemical Modeling on Y - SiO₂ and Zr- SiO₂ for the Negash granitoid

Modeling of Zr variation (Fig. 6. 14 (b)) indicates that this element behaved as an incompatible element in the mafic - intermediate rocks and become compatible in the most evolved magmas. As already mentioned, this change in behaviour of Zr could have been due to zircon separation at the advanced stage of evolution.

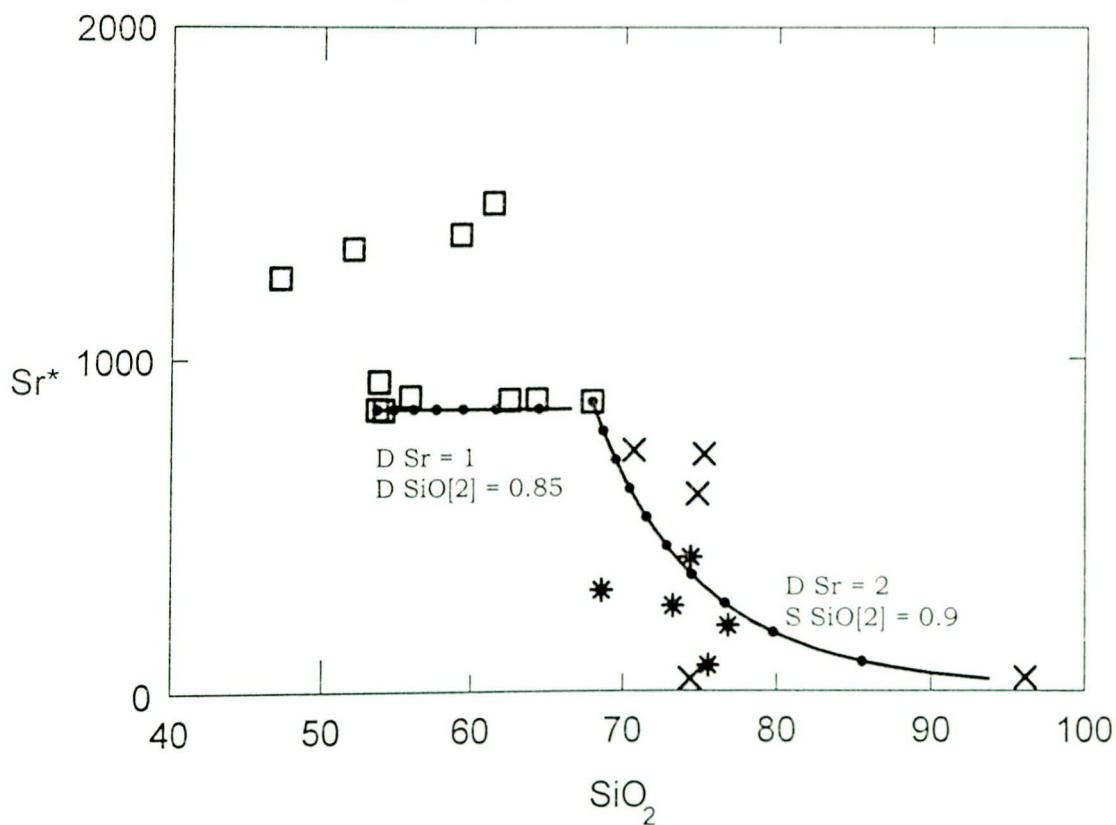
Ba has a behaviour very similar to Zr (Fig. 6. 15 (a)), in the sense that it is initially incompatible and becomes compatible in the most advanced stages of differentiation. The modification in the behaviour of Ba could be attributed to the separation of potassium feldspars that are the main minerals that host Ba. Biotite could also host some Ba, but its role has been excluded by the strongly incompatible behaviour of Rb.

The content of Sr (Fig. 6. 15 (b)) is anomalously high in a group of mafic rocks. It is likely that these high values could be the effect of plagioclase accumulation. This is in agreement with the positive anomalies of Eu observed in the REE patterns of some mafic samples. In other intermediate samples Sr behaves as a mildly compatible element ($D = 1$) to become more strongly compatible in the acid rocks where the role of feldspar fractionation becomes more important.

La shows an increase in the most mafic rocks with increasing evolution and decreases in the intermediate to felsic rocks. Accordingly, La and other LREE (not shown here) have a twofold behaviour during evolution. Since LREE are not hosted by any major rock - forming mineral, this modification in compatibility cannot be due to fractionation of any major mineral phase. However, apatite is able to host LREE in its lattice and its separation could account for the change in the behaviour of LREE. This is supported by the positive correlation between P_2O_5 and La and by geochemical modeling of these two element (see Fig. 6.16 (a) and (b)).

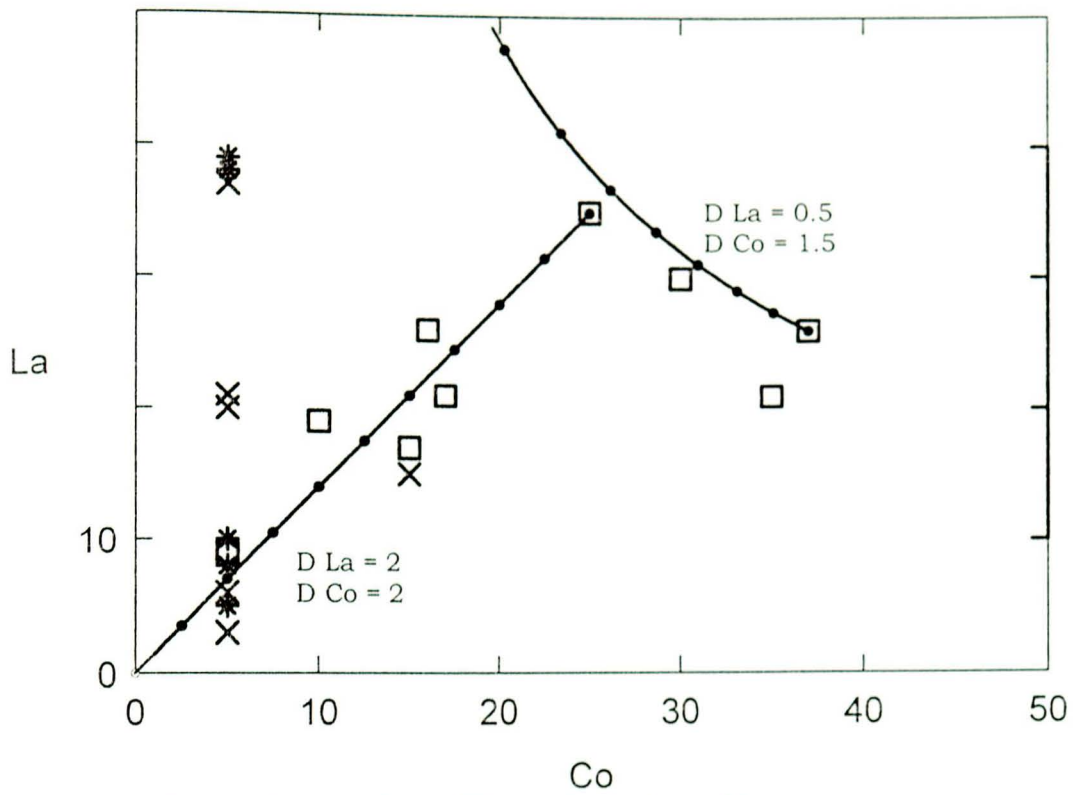


(a) FC model on Ba - SiO_2 at different D s for Ba.

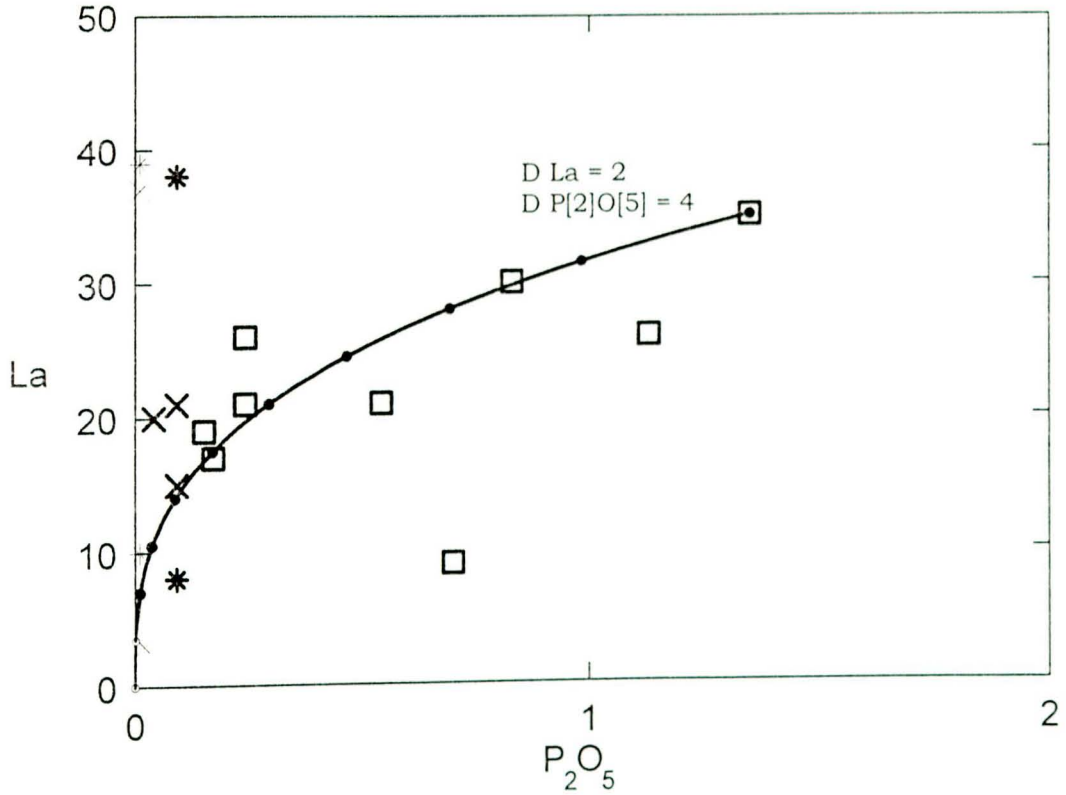


(b) FC model on Sr - SiO_2 at different D s for Sr.

Fig. 6.15. Geochemical modeling on Ba - SiO_2 and Sr - SiO_2 for the Negash granitoid.



(a) Fc model on La - Co at different Ds for La and Co.



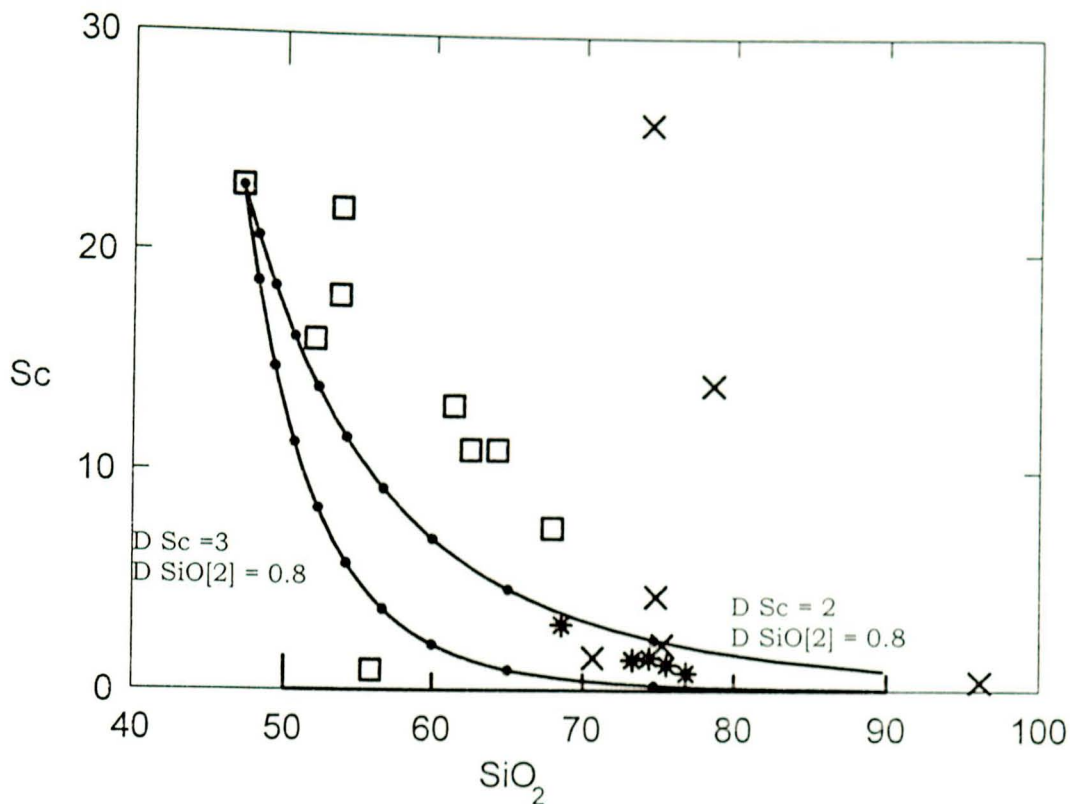
(b) FC model on La - P[2]O[5]

Fig. 6. 16. Geochemical Modeling on La - P[2]O[5] for the Negash granitoid.

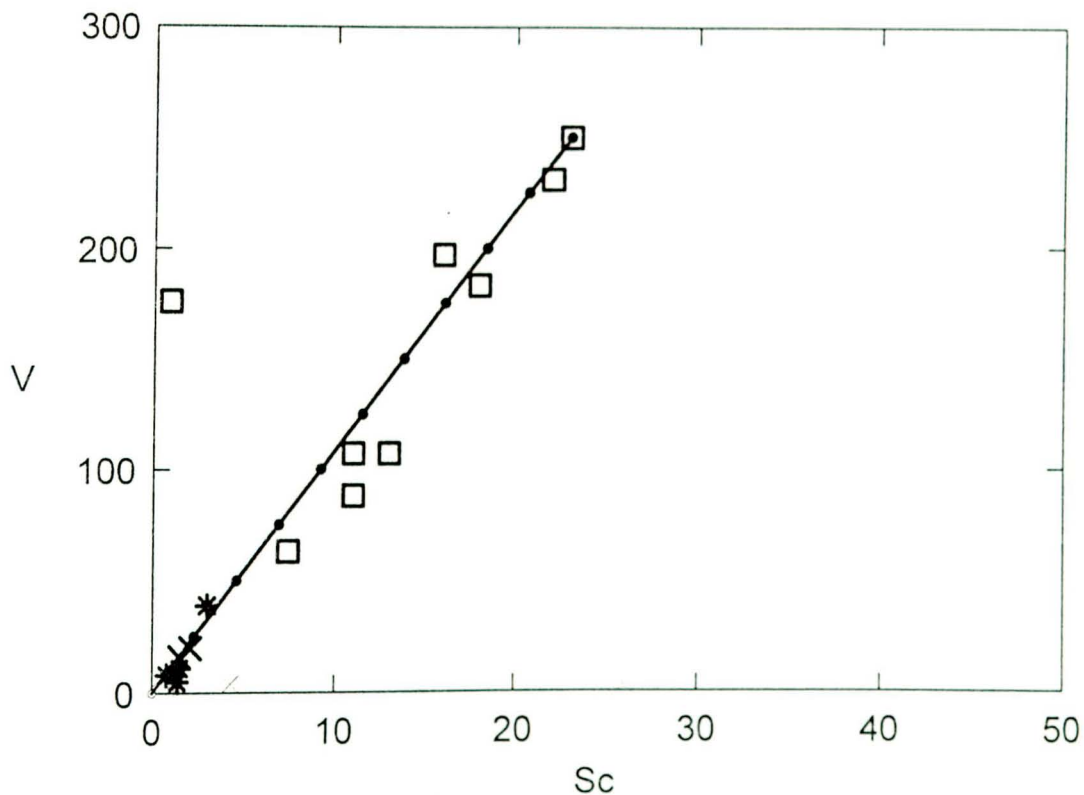
Ferromagnesian elements (Fig. 6. 17 (a) and (b)) display a regular decrease during evolution. This is consistent with the continuous separation of hornblende, even though the $D_{s/l}$ values used in the model are much lower than the values given by Gill (1981).

With regard to the most felsic rocks, most of the available data do not fit several of the evolution models which have been calculated to explain the evolution of the intrusive rocks. However, it is well known that residual liquids which are left behind crystallizing intrusive magmatic bodies have widely variable compositions (e.g. Clarke 1992 and references therein). This is observed in several granitoid bodies studied around the world (e.g. Bellieni et al., 1992). This particular behaviour of the residual melts arises from the fact that they represent interstitial liquids of extensively crystallized magmatic bodies. Hence, their chemical compositions may show extreme variations, depending on the composition of the crystallized minerals. Accordingly, the low K and Rb concentrations of some dikes indicate that they represent residual interstitial liquid of intrusive magmas which had already crystallized large amounts of potassium feldspar and biotite. On the other hand, the low Th of some dikes may indicate that these liquids were interstitial to rocks which had crystallized allanite or other Th-bearing minerals.

The residual interstitial liquids which are left at the latest stages of the crystallization history of plutonic rocks, are generally concentrated in the central parts of the intrusive bodies, which are the latest to crystallize. Hence, they are able to intrude the external rocks of the intrusion along fractures related to volume reduction of the cooling magma body. This explains why aplites and other strongly acidic rocks cut through all the lithologies that form the intrusive mass under study.



(a) FC model on Sc - SiO[2] at different Ds for Sc.



(b) FC model on V - Sc

Fig. 6. 17. Geochemical modeling on Sc - SiO[2] and on V - Sc for the Negash granitoid

IN CONCLUSION, the overall evolutionary history of the Negash pluton can be summarized as follows:

1. Mafic magma was emplaced within a magma chamber where it underwent fractional crystallization and moderate assimilation ($r = 0.3$) of upper crustal material.
2. The minerals which played a key role during magmatic evolution were:
 - a. Large amounts of hornblende which was a liquidus phase during the entire stages of evolution.
 - b. Plagioclase was also an important separating phase, especially in the intermediate- acid magmas
 - c. Alkali feldspar started to crystallize in the intermediate-acid magmas as indicated by the change of the geochemical behaviour of Ba.
 - d. Zircon and apatite were main crystallizing accessory phases which started to separate from the magma in the intermediate stages of evolution.
 - e. Biotite was not a major separating phase.
 - f. The latest residual liquids are represented either by true melt or by interstitial liquids whose unusual composition was very much a function of the mineral phases with which they were in contact.

The main petrologic implications of the above conclusions could be:

1. The continuous separation of large amount of hornblende did not allow the production of residual liquids rich in volatile components. This may be an explanation for the observation that pegmatitic rocks are not so abundant in the studied area, in spite of the fact that the outcropping rocks represent the apical part of the pluton which would be expected to be rich in volatiles.
2. The separation of accessory phases did not allow the residual liquids to be enriched in incompatible trace elements (Th, U, Zr, LREE) which could be found in the aplites and pegmatites.

CHAPTER 7**GEOCHEMICAL ANOMALIES AND ECONOMIC GEOLOGY****7. 1. GENERAL**

The search for mineral deposits in the present study area dated back to 1971 by the Ethiopian Institute of Geological Survey (Hagos 1971, Watters and W. Rufael 1971) when geochemical stream sediment sampling in the Mariam Adi Desta region (South east of Hauzien) revealed anomalous values for Zinc, Lead and some Copper which coincided in place. The origin of all these elements was ascribed by Beyth et. al (1971) to be hydrothermal and to be connected with the last phase of Mereb Granite intrusion (the granitoid stock). Although the Ethiopian Institute of Geological Survey intended to carry out further investigations in the area, it was not implemented and no other exploration works have been carried out in the area until the present investigation.

The present investigation revealed the occurrence of various pegmatitic and hydrothermal mineralizations which are locally significant. Although the sampling was not systematic, the obtained analytical data and field investigation in the granitoids and the country rocks allowed to identify geochemical anomalous samples and to pinpoint areas of potential interest for mineralizations. The stream sediment sampling data by the previous investigators is also interpreted and systematized to define the mineralized zone for Zinc and Lead.

7. 2. GEOCHEMICAL ANOMALIES

7. 2. 1. ZINC - LEAD ANOMALIES

At the beginning of the present investigation, the existing geochemical data on the area (although very scarce) were studied and systematized. The first stream sediment samples collected from the Adi Desta area by Assefa (1969) resulted in promising anomalies for Zinc (3300 ppm) and to a lesser extent for lead (80 ppm). Based on this result, further sampling by Hagos (1971) was carried out in the area and the results showed interesting patterns. Approximately 20 sq. km area was sampled and a total of 135 samples were collected. The sampling sites and the respective results for Zinc and Lead are represented in Fig 7.1 and 7.2. which are modified from Hagos (1971).

Zinc shows anomalies and the highest concentrations are found in a narrow zone trending North East. The highest value for Lead was found out to be 600 ppm and corresponds to the highest Zinc values. The maximum value for Copper was only 179 ppm and also corresponds to the highest values of both Zinc and Lead.

The same area was further investigated by Watters and W. Ruffael (1971) who sampled soils and rocks in addition to stream sediments. Two sampling programs showed similar results where the highest Zinc values reach up to 3300 ppm, the regional threshold being 140 ppm. Stream sediments resulted only in no more than 80 ppm

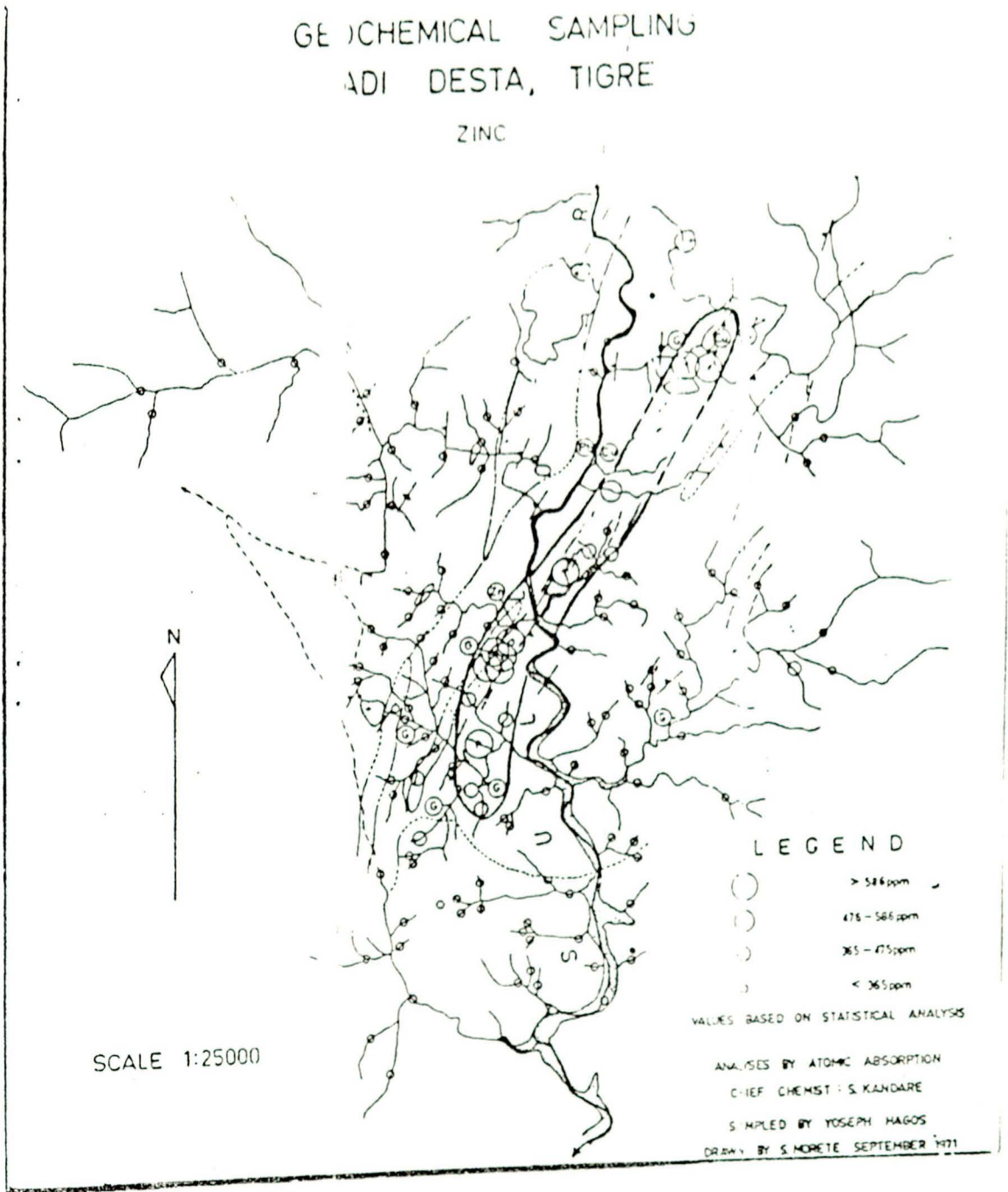
Soil samples showed up Pb concentrations to 275 ppm. The highest values for lead coincided with the highest values for Zinc. Silver assays were performed on the soil samples which were strongly anomalous for Lead and Zinc, and only the samples containing 3300

ppm Zinc was strongly anomalous at 1.5 ppm Silver. The area characterized by anomalous Zinc, Lead and Silver exactly coincided with the "Narrow Zone" of Hagos (1971) and covers about 8 sq. km.

The anomalous belt extends on both sides of the Suluh River. The drainage pattern in the area indicates that the possible sources of the anomalies in the soil and in the stream sediments are the ridges which are on either sides of the river close to the location of the stream sediments. Those ridges are drained by streams which are tributaries of the Suluh River.

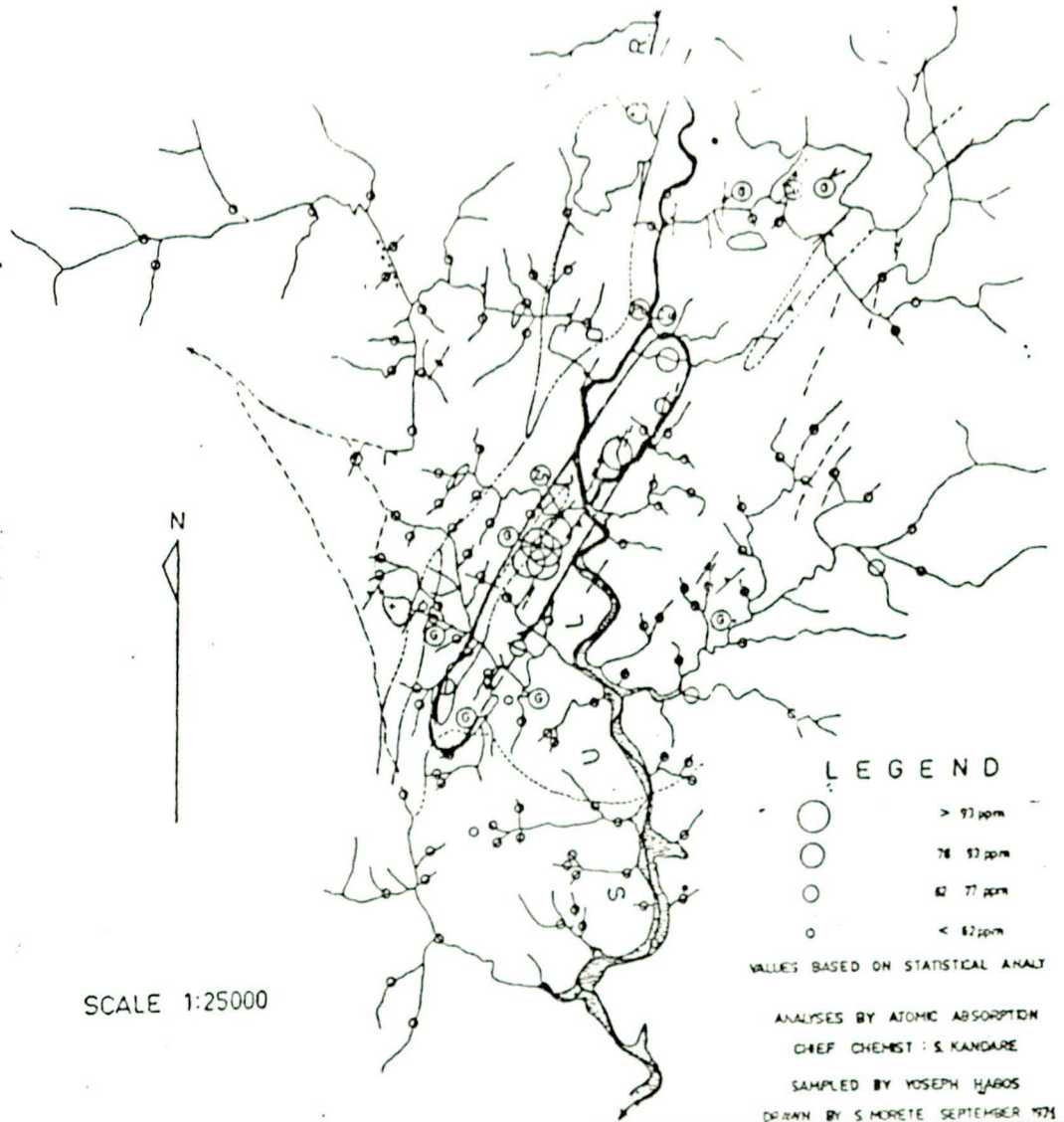
Those ridges have been investigated in some detail in the present study. They are constituted by chloritic metabasalts which are cut by quartz porphyry dikes. The ridge close to the highest anomalous zone is affected by an extensive belt of quartz veins trending N 30⁰ E almost parallel to the anomalous zone. The quartz veins are rich in specularites and iron hats (hematites). But they contain no indication of Zinc and Lead Sulphides (mineralizations). At the top of the ridge there are barite veins within potassic alterations.

GEOCHEMICAL SAMPLING
 ADI DESTA, TIGRE
 ZINC



GEOCHEMICAL SAMPLING ADI DESTA, TIGRE

LEAD



SCALE 1:25000

LEGEND

- > 97 ppm
- 78-97 ppm
- 62-77 ppm
- < 47 ppm

VALUES BASED ON STATISTICAL ANALY

ANALYSES BY ATOMIC ABSORPTION

CHIEF CHEMIST: S. KANDARE

SAMPLED BY YOSEPH HAGOS

DRAWN BY S. MORETE SEPTEMBER 1971

7. 2. 2. GEOCHEMICAL ANOMALIES BASED ON TRACE ELEMENT ANALYSES

One of the geochemical problems of the basement rocks for the purpose of the present thesis is that of detecting possible geochemical anomalies that can be used as tools for future detailed geochemical prospecting. Geochemical anomalies can be detected only when the background values for the various rock types has been established. In several cases the Clark of the different elements for various rock types is used as a background value. In other cases the background is calculated from data obtained by extensive and statistically significant data obtained for rocks from the region. Obviously, this requires that a large number of samples, collected from different localities of a given region, must be analyzed.

For the purpose of the present study a limited amount of samples were collected away from the pluton and in zones that did not show evidence of any kind of mineralization. The values of these rocks will be used, in conjunction with the Clark for various types of igneous and sedimentary rocks and of average crustal values (Taylor and McLennan, 1985), as reference values to establish geochemically anomalous samples. As suggested by several authors (e. g. Rose et. al, 1979), a value more than twice the reference values of appropriate rock types will be considered as anomalous.

Table 7. 1. reports abundances of some economically important trace elements for the upper continental crust, lower continental crust, and several types of igneous and sedimentary rocks (Taylor and McLennan, 1985; Rose et al., 1979). Data for the rocks collected away from the Negash pluton in non-mineralized zones are also reported. The comparison between these data and those obtained for the analyzed intrusive and

metamorphic rocks allows to draw some conclusions on the samples that show geochemical anomalous concentrations of the elements under consideration.

Cr - The abundance of this element in the analyzed metamorphic samples range from 140 to 10 ppm. None of these values can be considered as anomalous, inasmuch as they fall well within the range of values of the reference rocks. The same worth true for the mafic intrusive rocks, except perhaps for sample TG 52 that shows rather high Cr = 589 ppm, a value that is not uncommon in many mafic rocks. Instead, the granites and granodiorites display Cr abundances that may be anomalous if compared with average values of acid rocks. However, it is likely that these anomalous concentration may be an artifact of sample preparation acquired during crushing in the steel jaw crusher. Based on this, it must be concluded that this element does not show significant anomalies in the analyzed samples.

Ni and Co - No anomalous samples have been found either among the metamorphic or the magmatic rocks.

Zn - Anomalous value has been found in one metavolcanic rock and strongly anomalous concentrations have been detected in a silicified metavolcanic rock. Both samples were collected southwest of the pluton along the Suluh river. Among intrusive rocks an aplite and a pegmatite sample are strongly anomalous.

Table 7.1 Abundances of trace elements in various rocks (references) and the Negash metamorphic and intrusive rocks

Elements	lower crus	upper crus	Crust	Ultramafic	Mafic	Granites	sandstone	Shale	Metamorphic rocks away from the pluton						
									TG 79	TG 81	TG82	TG83	TG95	TG96	
Cr	235	35	185	2980	170	4.1	53	90	46	19	24	87	110	130	
Co	35	10	29	110	48	1	0.33	19	12	7	11	29	5	10	
Ni	135	20	105	2000	130	4.5	2	68	5	50	50	50	50	50	
Zn	83	71	80	58	94	51	40	100	60	50	50	50	50	50	
As	0.8	1.5	1	1	1.5	2.1	1.2	12	2	2	2	2	2	2	
Mo	0.8	1.5	1	0.3	1.5	1.3	0.2	2.6	5	5	5	5	5	5	
Sn	1.5	5.5	2.5	0.5	1.5	3	0.6	6	100	200	100	100	100	100	
Sb	0.2	0.2	0.2	0.1	0.1	0.2	1	1.2	0.8	0.4	0.2	1	0.6	0.2	
Ba	150	550	250	0.4	330	840	170	550	710	370	530	100	1100	340	
La	11	30	16	4	17	55	7	39	12	21	13	11	33	9	
Yb	2.2	2.2	2.2						1.8	8.5	8.5	1.6	7.4	2.2	
Ta	0.6	2.2	1	0.018	0.48	3.5		3.5	1	1	1	1	1	1	
Au (ppb)	3.4	1.8	3	3.2	3.2	2.3	5	4	7	3	3	3	3	3	
Th	1.06	10.7	3.5	0.004	2.7	10	5.5	12	1.6	4.4	1.9	2.1	6	2	
U	0.28	2.8	0.91	0.03	0.53	3.9	1.7	3.7	0.5	1.9	0.5	0.5	2.7	0.5	
Negash Metamorphic Rocks															
Elements	Anomalous samples					Strongly anomalous samples									
Cr	no					no									
Co	no					no									
Ni	no					no									
Zn	TG 127					TG 86									
As	TG 71, TG 120, TG 124					TG 89, TG 118									
Mo	no					TG 46									
Sn	TG 46, 56, 62, 63, 71, 75, 76, 77, 83, 86, 100					TG 47									
Sb	TG 92, TG 100					TG 89									
Ba	TG 46, 63, 88, 93, 115, 120, 124, 127					TG 71, TG 106, TG 89									
La	TG 77					TG 88									
Yb	no					no									
Ta	TG 124					no									
Au	TG 102, 115, 120,					TG 62, TG 63, 92, TG100									
Th	no					no									
U	TG 46, 63, 77, 93, 115, 118, 124, 125, 127					no									
Negash Pluton															
Elements	Diorites and tonalites					Granites (including pegmatites and aplites)									
Cr	TG 52					all are strongly anomalous									
Co	no					below detection limit									
Ni	no					below detection limit									
Zn	no					TG 50, 61									
As	no					TG 58									
Mo	no					TG 53, 57, 65, 112									
Sn	all are anomalous					TG 48									
Sb	no					no									
Ba	TG 48, 49, 64, 104, 110,					no									
La	TG 64, 114					no									
Yb	no					no									
Ta	no					below detection limit									
Au	no					no									
Th	TG 114					no									
U	TG 49, 114					no									

As - Several samples of metamorphic rocks have shown anomalous values. Instead, the intrusive rocks have not shown anomalous As concentrations, except for a single sample. The anomalous metamorphic rocks are all metabasalt and come from different areas.

Mo - No significant anomalies have been detected in the metamorphic rocks. Instead, several samples of acid intrusive rocks are anomalous.

Sn - There are a several samples of both the intrusive and the metamorphic sequences that show values above the detection limit of 100 ppm. These samples are to be considered as anomalous for tin, since the background values for this element is at a level of a few ppm for almost all the rock types. Based on these criteria, most of the acid igneous rocks are anomalous for Sn. Among the metamorphic rocks, the largest number of anomalous samples come from the contact with the pluton, event though a few samples collected away from the intrusion also have anomalous concentrations. It is of interest that there is no particular concentrations of anomalous samples along the Suluh River valley, which has furnished the largest number of anomalous samples for several elements. However, it must be pointed out that, because of the high detection limit of the INAA method, the anomalous samples for Sn could be much more abundant than presently recognized.

Sb - A few samples of metamorphic rocks have shown anomalous values. These samples all come from the Suluh River valley.

Ba - Shows anomalous values in several samples. However, it must be recalled that Ba displays very variable concentrations in igneous and metamorphic rocks and it is difficult to establish which concentrations have to be considered as anomalous. However, it must be mentioned that, among metamorphic rocks, the highest Ba value have been found in the rocks from a roof pendant on the central part of the pluton where barite veins have been observed. Among intrusive rocks, high values are shown by some mafic rocks. However, these values do not necessarily indicate secondary processes, but may be pristine values of mafic rocks which often show concentrations as high as 2000-3000 ppm.

REE - Few samples are anomalous. These include TG 89 which is a silicified metavolcanic breccia from the Suluh River valley.

Au - Several metamorphic rocks display anomalous gold concentrations. These consist mostly of intermediate metavolcanics. The anomalous samples mostly come from the Suluh River valley. Two samples are contact rocks collected on the eastern part of the pluton. No anomalous samples have been found among the intrusive rocks.

Th and U - Uranium shows anomalous concentrations in several metamorphic rocks and in two intrusive samples. The largest number of samples come from the Suluh River valley, with two samples collected from the roof pendants on the central part of the pluton and from the eastern contact. Th does not display anomalies, except in one single diorite sample.

7. 3. CONCLUSIONS

From the data illustrated above several conclusions can be drawn on the mineralization events which have affected the area under investigation. The data also furnish important information on the potentially most interesting area in which further geochemical and geological exploration should be carried out.

1 - The intrusive rocks, including the most evolved ones, have not shown significant geochemical anomalies in most of the elements under consideration. Exceptions are Zn, Sn, and Mo. Among these, Mo shows no anomalies in the metamorphic rocks. These data suggest that the evolution of the Negash magmatic body generated limited mineralizing fluids in the latest residual rocks and in the country rock. Sn and Zn mineralization, which are detected in the host rocks and, to some extent in some granitoids, appear to be the only elements whose geochemical anomalies are genetically directly related to the magmatism. Ba anomalies could be an effect of latest most magmatic activity, as discussed in Appendix A. Hence, the granitoid rocks are not strongly metallogenic. This conclusion, together with the scarcity of late stage fluid rich rocks (e.g. pegmatites) may find an explanation in the particular evolutionary history of the magma. As shown in Chapter 6, the magmatic evolution of the Negash pluton has been dominated by fractional crystallization and AFC, with heavy separation of hornblende. The strong role of this hydrated mineral as separating phase could have created the conditions for the formation of volatile-poor residual liquids. The formation of relatively dry residual melts could be a main cause for the scarcity of

pegmatites and the lack of significant mineralizing events directly related to the plutonic event.

2. Many metamorphic rocks have anomalous values for the considered trace elements. The most striking evidence which comes out from the data is that the largest amount of the anomalous samples come from the restricted belt of the Suluh River valley. In this area of intensive secondary metasomatism, anomalies of Au, U, Sb, Ba, As, Zn have been detected. Since, as previously suggested, mineralization for these elements do not appear to be directly related to the pluton, it must be concluded that the source of fluids and their solute load are to be located in the metamorphic rocks. In this case, it seems probable that the magmatic event provided the energy but not the mass of the mineralizing agents. The fact that the geochemical anomalies are concentrated along the Suluh River is simply a consequence of the presence of the fracture zone in this area. This hypothesis is strengthened by the fact that samples with anomalous values of Sn, which have been found to be directly related to igneous activity, are not concentrated along the Suluh River valley. This confirms that the fluids which were responsible for metasomatism in the Suluh fracture zone are of metamorphic origin. Some elements such as As display anomalous concentrations also in rocks which have been collected away from the pluton. This could be taken to indicate some kind of mobilization during metamorphism. Alternatively a larger dispersion halo for the mobile As during metasomatism could be envisaged.

Therefore, the Suluh River valley near to the pluton represents the most interesting area from an economic point of view. Hence, a detailed exploration geochemistry investigation is strongly advisable in this area. This conclusion is also supported by detailed

field exploration which has been carried out in the final part of the studies of the present thesis and the results are described in Appendix A.

Since two anomalous samples for Au have been found in the country rocks at the eastern border of the intrusion, some additional geochemical investigations is advisable also in this area.

CHAPTER 8**CONCLUSIONS AND RECOMMENDATIONS**

The field observations and the analytical data obtained in the present work allow the following conclusion to be drawn:

1. The Negash area consists mostly of greenschist facies metavolcanic rocks with minor intercalations of metasedimentary rocks. The metamorphic rocks are affected by folding and by two generations of faulting with NNE - SSW and WNW - ESE trends.
2. The metavolcanic rocks display geochemical compositions akin to calc alkaline basic to felsic rocks and tholeiitic arc basalts. This suggests an emplacement in an island arc environment.
3. The metavolcanic rocks are cut by a circular, undeformed, discordant pluton which generated thermal metamorphic effects on the country rocks resulting in local hornblende - hornfels facies rocks at the contact aureole. The western contact between the pluton and the country rock is linear and lies along a fault line that forms the Suluh River valley.
4. The pluton consists of gabbroic diorites, diorites, quartz diorites, tonalites, monzonites and granodiorites with minor granitic, aplitic and pegmatitic dikes. The overall composition of the rocks is typically high-potassium calc alkaline. Discriminant element abundances suggest an intrusion in a volcanic arc environment.

5. Model on the structure of the pluton based on field and petrological data suggest that the pluton consists of prevailing mafic rocks, with minor granodiorites which are concentrated towards the top. The outcropping part of the intrusion represent the top most part of the granitoid body.
6. Geochemical modeling based on major and trace elements suggest that the intrusive rocks were differentiated from a mafic magma by fractional crystallization and AFC. Hornblende was the major separating mafic phase. Alkali feldspars and accessory phases such as apatite, zircon and allanite played a role during the intermediate to late stages of magmatic differentiation.
7. The plutonic rocks, including the most differentiated aplites and pegmatites, do not show significant geochemical anomalies except for a few elements such as Sn and Zn. This leads to suggest that the magma did not play an important role in generating mineralizations in the area. Instead, the intrusion may have furnished the heat which triggered fluid circulation and elemental mobilization in the country rocks.
8. Geochemical anomalous samples for Au, Zn, U, As, and Ba were found to be concentrated along the western boundary of the pluton, the Suluh fault line. The fault provided the ease through which the metasomatic fluids enriched the area with metals. Further geological and geochemical investigations should be directed to this zone.

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APPENDIX A

FIELD OBSERVATIONS IN SELECTED AREAS

The field investigation and the preliminary data obtained on the analyzed samples indicated that the metavolcanics in the western and south western parts of the pluton are characterized by a considerable hydrothermal activity and geochemical anomalies. Other interesting metasomatic processes have been observed in some roof rocks and at the contacts between the intrusion the metavolcanics. This has prompted additional field work aimed at better defining the rock types and the metasomatic products occurring in these areas. This additional work has been carried out in the final part of the present thesis and is here briefly summarized.

A. 1. PEGMATITE VEINS AND RELATED MINERALIZATIONS

Pegmatite veins are concentrated in two major zones within the intrusion : at the contact between the granodiorites and the metavolcanics and as pegmatite stockworks affecting the diorites close to the contact with the tonalites. The contact pegmatites are simple, non - mineralized types while the pegmatite stockworks are a bit differentiated and host some minerals.

The contact pegmatites occur in two main orientations : normal and tangential to the contact resulting in radial structures. The pegmatites are composed of only K - feldspars, quartz and big muscovite crystals and exhibit characteristics myrmectic textures. These pegmatites are generally simple except some traces of tourmalines in some veins which crossed the metavolcanics.

The pegmatites affecting the granodiorites show transition to aplites within the same dike. Some pegmatites show zoning from fine grains at the border to coarser grains towards the center indicating the coexistence of the magmatic liquid and the crystalline phases (quartz, orthoclase, mica) together.

The pegmatite stockwork within the diorites forms a pegmatite field of considerable extent and occurs in two different facies :

1. Simple pegmatites composed of quartz, feldspars, biotite with pegmatitic or graphic textures.
2. Albitized and epidotized pegmatites which are highly differentiated (or altered) near to the contact with the diorites. These pegmatites are composed of a considerable amount of epidote, albite, clevelandite, with some tourmalines, acicular rutiles, and hematite, in addition to the quartz, K -feldspar, muscovite and biotite. Pegmatites are, in turn, affected by quartz veins stained with greenish and black impregnations.

A.2. QUARTZ VEINS AND RELATED MINERALIZATIONS

The country rocks and the granitoid stock are much affected by quartz veins of variable extent, orientation and character, and three important types of quartz veins are distinguished :

1. milky quartz veins affecting the country rocks, with out any mineralization,
2. mineralized quartz veins, veinlets and stockworks affecting the country rocks, the granitoid, the quartz porphyry dikes, the aplites and the pegmatites, and
3. quartz veins which are exclusively related to potassic (red) alterations.

BARREN QUARTZ VEINS

The metavolcanics away from the contact to the granitoid are affected by a series of quartz veins which are composed of pure milky quartz and are barren except for some oxidized pyrites resulting in black staining. Such quartz veins which range from 5 cm to about 1 m thickness are widespread and frequent in the western and northern parts of the pluton, within the metavolcanics. In some areas, like the western part, these veins form extensive belts of considerable extent. The thickness and frequency of these veins decreases towards the contact. These veins have an orientation which is almost parallel or at very low angles and rarely across the foliation direction of the metavolcanics, indicating that they are formed by lateral secretion from the country rocks and they are not related to the granitoid

stock. There are also some barren quartz veinlets of thickness 5 - 10 cm which are folded with country rocks, providing further evidence for a syn-metamorphic genesis of barren quartz veins.

MINERALIZED QUARTZ VEINS

Either side of the contact is characterized by high concentration of quartz veins which are rich in hematites usually with specular texture (as Specularite). These quartz veins occur as single large veins, veinlets and stockworks ranging in thickness from a few mm up to half a meter. The quartz veins occur at various orientations and some recorded orientations include N - S, E - W, N10⁰ E, N20⁰ E, N30⁰ E, N60⁰ E, N320⁰ E.

In the western and south western parts of the studied area, these quartz veins are widespread. Close to the southwestern contact the veins become rich in magnetites which, at the surface, are changed to brownish hematites. In places, close to the quartz veins, there are veins of magnetites (1 cm - 10 cm thick) filling fractures parallel to the foliation direction of the country rocks.

At the western contact up north, there is an extensive field of quartz veins, veinlets and stockworks affecting the metavolcanics, with altered pyrites, hematites, some other metallic minerals and are associated with feldspars and a considerable amount of calcite.

In the vicinity of the area where there is a recorded Zn - Pb anomaly from stream sediments (See Fig 7.1.) the quartz veins become particularly rich in iron oxides (hematites) forming the Iron Hats which form veinlets having a thickness of up to 3 cm.

Within the granitoid stock, the diorites are much affected by stockworks of the mineralized quartz veins and veinlets, especially near to the western contact and to the tonalites and granodiorites. These hematite rich quartz veins also affect the pegmatites, aplites and quartz porphyries at various orientations.

MINERALIZED QUARTZ VEINS WITHIN POTASSIC ALTERATIONS

The metavolcanics in the southwestern part of the investigated area are brecciated highly silicified and occasionally migmatized rocks. These rocks are frequently affected by

extensive potassic metasomatism recognizable from the red colour of the rocks. These potassic alterations which have formed K - feldspars enclose quartz veins, veinlets and stockworks that are particularly rich in specularites which, in places, form their own veinlets of thickness up to 2 cm within the quartz veins and potassic metasomatic rocks.

These potassic alterations which range in thickness from half a meter to 15 m and extend along the strike for a considerable distance, cut the brecciated rocks usually at low angles and occasionally at large angles (some recorded orientations : N310⁰ E, N195⁰ E, N20⁰ E, N30⁰ E). The potassic alterations and the enclosed quartz veins are affected by minor faults, vertical joints, and minor fractures along which the hematites are concentrated. The detailed sketch of one such dike is represented in Fig. A.1. Plates A. 1 and A. 2. are photographs of such potassic alterations with quartz veins.

The potassic alterations also host some barite veins which are almost barren.

The association of potassic alteration with relatively high temperature minerals like hematite within quartz veins is a favourable geologic condition for gold mineralization if there is any source rock nearby (Valera, Person. Comm.), and the geochemical analysis of the country rocks near the contact revealed 4 - 14 ppb gold which is the highest value among all the analyzed rock samples, supports this suggestion.

A. 3. BARITE - FLUORITE MINERALIZATIONS

The southwestern part of the mapped area is characterized by extensive Barite - Fluorite mineralizations. There is also one barite vein in one of the roof pendants within the pluton. The most important mineralized zones are described, along with their specific locations below :

1. Location : at the top of a roof pendant within the intrusion

Thickness : 30 cm extending for about three meters

Orientation : N30⁰ E cutting the hornfelses

The barite vein contains some altered black minerals and geochemical analysis revealed 41,000 ppm Ba. Host hornfelses contain 2,200 ppm Ba.

LEGEND








-  UNALTERED ROCK
-  QUARTZ VEIN PARTIALLY FILLED BY HEMATITE
-  POTASSIC ALTERATION
-  FRACTURE
-  VERTICAL JOINT
-  INCLINED JOINT
-  FRACTURE FILLED BY HEMATITE

Fig. A-3 Detail of mineralized veins enclosed within potassic alterations.

LOCATION
N13°51.374'
E039°50.635'

20 CM

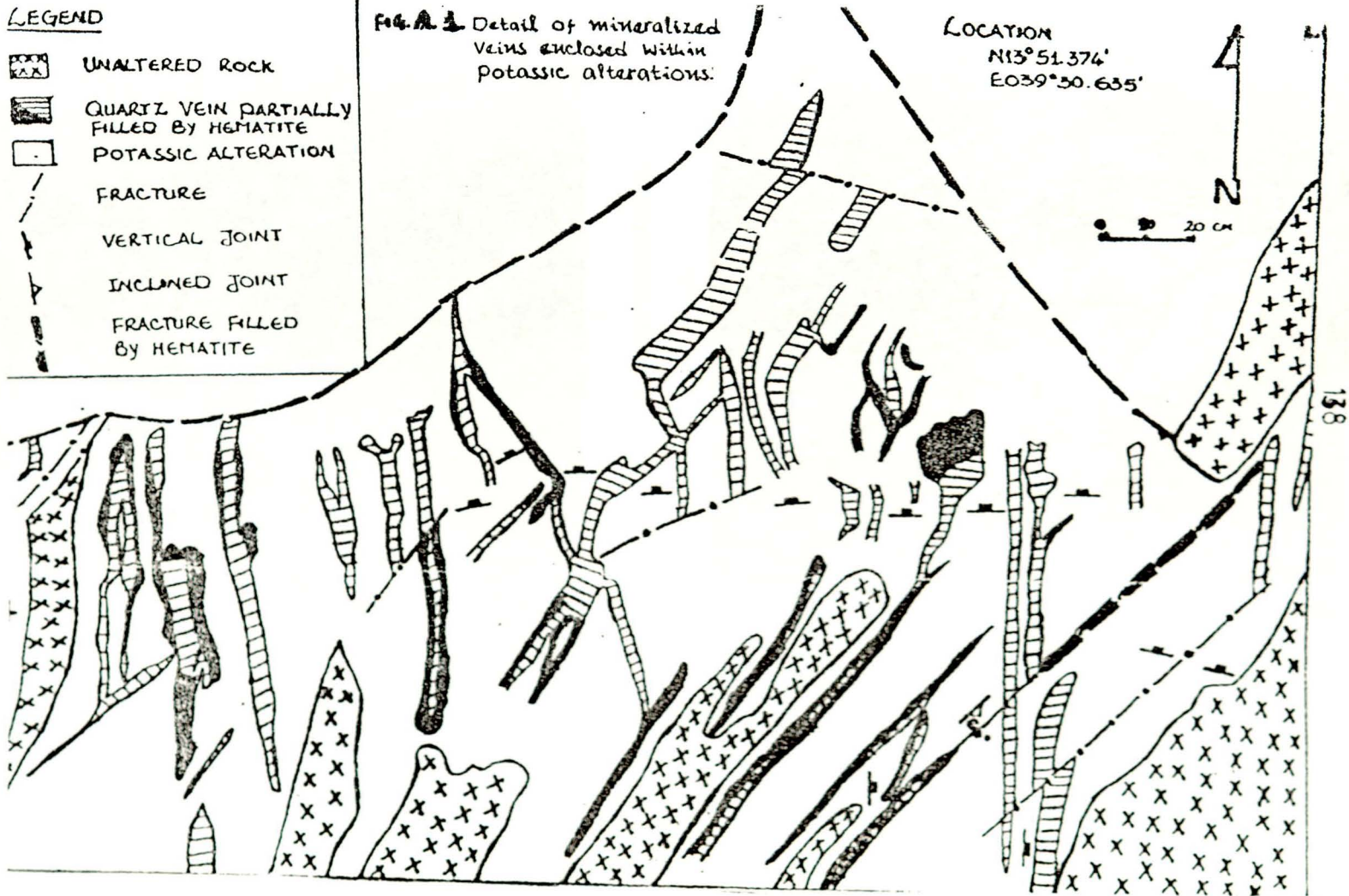




Plate A. 1. Quartz veins within potassic alteration. The quartz vein hosts hematite (dark)

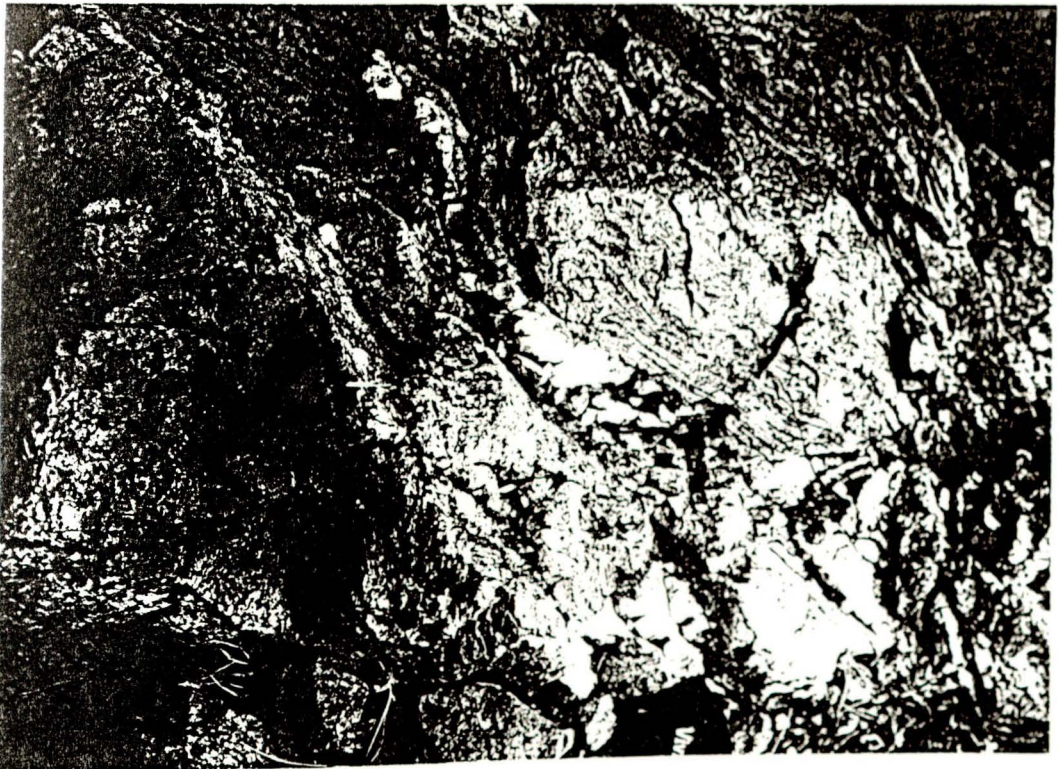


Plate A. 2. Potassic alteration (flesh red) that shows well - developed feldspatization

2. Location : on the eastern flank of the Suluh river
 Thickness : 5 cm extending for about 20 m along the strike
 Orientation : $N230^{\circ} E$ (NE - SW)
 The barites occur as veins and veinlets enclosed within potassic alteration. In places, it is associated with quartz veins. Barite exhibits a weathered crust at its surface.
3. Location : $N13^{\circ} 51.404'$ $E039^{\circ} 30.520'$ (at the top of a hill)
 Orientation : E - W, crossing foliation of the country rocks at large angles and are discordant to the general structure.
 The barite veinlets form stockworks (as breccia cement) filling the fractures in the country rocks, and are enclosed within the potassic alterations.
4. Location : $N13^{\circ} 57.329'$ $E039^{\circ} 29.708'$
 Thickness : 30 cm
 Orientation : E - W
 The barite vein is enclosed within a very thin zone of potassic alteration cutting the metabreccias and metabasalts. It is accompanied by many other small veinlets of similar orientation.
5. Location : $N13^{\circ} 51.618'$ $E039^{\circ} 30.551'$
 Thickness : 1.6 m
 Orientation : $N120^{\circ} E$
 The barite forms stockworks associated with quartz veins within potassic alterations (Plate A. 3.), and are subparallel to each other. The barites affect the metabreccias. Up the slope towards the top, the barite occurs as prominent sets of veinlets criss crossing each other but generally oriented E - W and almost N - S directions respectively, affecting the metabreccias which are generally oriented at $N10^{\circ} E$.
6. Location : $N13^{\circ} 51.671'$ $E39^{\circ} 30.322'$ (at a village which is named Maichew)
 Thickness : Vein up to 1 m and the mineralized belt up to 12 m, extending for about 100 m along the strike.
 The barite veins outcrop at the top of a hill cutting the brecciated rocks at low angles. The barites which are occasionally accompanied by fluorites occur as big veins, small patches and as cements filling the fractures in the country rocks. The

barites and the fluorites show very distinct radial and acicular textures. The details of this mineralized belt is represented by a sketch map in Fig A.2.

7. Location : $N13^{\circ} 51.371'$ $E039^{\circ} 30.491'$

Thickness : 50 cm extending for about 30 m along the strike

Orientation : $N50^{\circ} E/45^{\circ} NW$

This barite vein outcrops at the top of a hill but there are barite veins on both sides of the slope oriented $N35^{\circ} E$ and $N60^{\circ} E$, with 30 cm and 60 cm thickness respectively, increasing in thickness up to 1.5 m along the strike, towards the top. The thickness decreases down the slope and finally changes to small veinlets which fill fractures within the country rocks. The veins are all generally dipping towards northwest.

In the same locality but at the top of an adjoining ridge there is a zone of barite mineralization where a barite vein oriented at $N30^{\circ} E$ is accompanied by a large number of barite veinlets having a general orientation of $N60^{\circ} E$, but within the belt (the stockwork) the veinlets are criss crossing each other at various angles.

The outcrop extends for about 60 m and the thickness of the veins ranges from a few cm to about half a meter. The barite stockwork is hosted by metatuffs.

8. Location : $N13^{\circ} 51.515'$ $E039^{\circ} 30.338'$

Thickness : 40 cm

Orientation : $N50^{\circ} E$ but changes direction because of some bending.

The barite vein shows a peculiar feature where red, massive barite encloses a light purple coloured, acicular and radial barite (pure barite) inside.

In the same locality, there are barite veinlets mixed with quartz veins forming a belt generally extending at $N35^{\circ} E$. The top of the slope is affected by an intricate network of barite veinlets which completely filled the fractures within the host rocks. In addition there is a barite vein oriented at $N75^{\circ} E$ which contains some fluorite cubes that fill the interior part of the vein.



Plate A. 3. Barite veinlets within potassic alteration and associated quartz veinlets.

9. Location : N13⁰ 51.660' E039⁰ 30.200'

Thickness : 50 cm

Orientation : N20⁰ E

The barite vein which outcrops at the side of a ridge contains many fluorite cubes, fluorite and barite mixtures, and pure barite and sometimes it occurs as barite cement in the country rocks.

10. Location : N13⁰ 51.820' E039⁰ 30.178'

Thickness : 25 cm

Orientation : N 310 0 E

This barite vein which outcrops at the top of a ridge contains only pure barite.

11. Location : N13⁰ 52.002' E039⁰ 30.166'

Thickness: 70 cm but weathered in the middle along its strike

Orientation : N 25⁰ E

The barite contains many fluorite cubes some of which are up to one cm in size.

There are a series of similar barite veins in the same locality, exposed along a track.

The southwestern part of the mapped area is constituted by brecciated rocks and metarhyolite close to the contact and metabasalt, metatuff away from the contact. These rocks form a series of ridges elongated parallel or subparallel to the foliation direction of the rocks, and are affected by a series of NW - SE trending faults which are subparallel to the main "Wukro Fault Belt" which separates the Precambrian rocks from the "Mekele Outlier". The ridges form a series of down faulted surfaces on either side of the Suluh river, although the throws are not considerably large and the fault faces are totally weathered away. The hill tops, then, represent palaeosurfaces. The barite - fluorite and the Galena - Barite mineralizations are concentrated at these surfaces. The barite is extensive towards the tops of the slopes but towards the foots of the slopes, the barite veins become less extensive, small in thickness, less frequent and finally cease to exist while the quartz veins composed of the specular hematites become more extensive and frequent.

This clear relationship indicates that the barite, which is a low temperature mineral is not associated with main phase of mineralization that gave rise to the hematite rich quartz

veins, but is a late stage mineralization related to meteoric water which could be heated by the high temperature of the cooling granitoid intrusion. This is supported by the presence of barite veins at the top of the cap rocks (hornfelsic roof pendants) within the pluton.

A. 4. HEMATITE - BARITE MINERALIZATION

Although a swath of anomalous values for Lead in addition to that of Zinc was indicated from stream sediment and soil samples in the Adi Desta area by previous investigators (like Hagos 1971, Watters and W. Ruffael 1971) no insitu mineralization was identified. During the present investigation, in addition to the detailed description of the mineralized quartz veins, potassic alterations and barite veins, extensive Barite - Fluorite and Hematite - Barite mineralizations (which looks very much like galena) have been identified in the mapped area, for the first time.

The Hematite - Barite mineralization outcrops at a palaeosurface which is close to the contact between the country rocks and the pluton.

Location : N13⁰ 52. 863' E039⁰ 31. 059' (at a locality known as Zeban Debreselam)

Thickness : Maximum 4 m and continues for about 120 m along the strike.

Orientation : Almost E - W.

The hematite and barite occur as veins of 30 - 50 cm thickness and filling the fractures in the brecciated rocks as cements separated by unmineralized thin septa of few cm thickness.

Although no geochemical analyses were made for Pb, the field investigation revealed a close relationship between galena (?) and barite and the galena is concentrated at the surface indicating that it was concentrated by similar process that concentrate barium in barite veins. Sources of the lead anomalies in the stream sediments and soil samples can be ascribed to these galena (?) mineralizations.

A. 5. FELDSPAR DEPOSIT

Apart from the above described mineralizations, the metavolcanics in the South - western part also host a feldspar deposit of considerable extent.

At a location N13⁰ 53. 227' E039⁰ 30. 376' (at a locality named Endaba Abun) on the western flank of the Suluh river valley, there is a peculiar type of rock that is composed of pure feldspar with a very little quartz, and has a very pure white colour. The deposit consists of two bodies with a thickness of around 100 - 120 m and about 30 m. They are separated by a gap of about 50 m of metavolcanics. The deposit extends for about 2 km at a general trend of N 20⁰ E/ 28⁰ NW. The feldspar rich rock which is highly indurated and foliated is cut by small quartz and aplite veins with various orientations.

APPENDIX B

PETROGRAPHIC DESCRIPTION OF SOME SELECTED SAMPLES

B. 1. INTRUSIVE ROCKS

- 1. Sample :** TG 58, collected from the contact zone, eastern side.
- Handspecimen :** Granodiorite composed of large crystals of feldspars with clearly observable quartz, and mafic minerals.
- Identified Minerals :** plagioclase feldspars, K - feldspars, quartz, some hornblende, rare muscovite, epidote and opaque minerals.
- Texture :** The rock is phaneritic hollocrystalline dominantly constituted by plagioclase feldspars forming large euhedral to subhedral crystals with albite, albite - carlsbad and albite - pericline twinning and myrmectic intergrowths with quartz. Some plagioclases exhibit sieve textures while the dominant crystals are characterized by prevalent normal and oscillatory zoning. There are also large microcline crystals which exhibit characteristics cross - hatched (tartan) twinning (albite and pericline laws) very distinct under crossed polars. The biotites form subhedral to euhedral crystals up to 2 cm size, with distinct and perfect basal cleavage. Some of the biotites contain quartz inclusions.. The hornblendes are generally associated with the biotites. Some of the hornblendes have a biotite rim. Others show penetrating boundaries with the biotites. The muscovites and epidotes are rare and very fine - grained and recognized only at higher magnifications. They are clearly secondary in origin. Most of the opaque minerals are enclosed within the biotites.
- Accessory Minerals :** Zircon, apatite and sphene.
- Estimated Composition :** plagioclase : 50 %, K - feldspar : 10 %, quartz : 20 %, biotite : 15 %, hornblende : 7 %, muscovite and epidote : 1 %, opaque minerals : 2 %. (Modal composition)
- Petrographic Name :** Biotite - Granodiorite.

- 2. Sample :** TG 70, collected from the contact between the granodiorites and tonalites.
- Handspecimen :** Granodiorite which contains more mafic (black) minerals and is more melanocratic than the previous sample.
- Identified Minerals :** plagioclases, K - feldspars, quartz, biotite, Hornblende, rare muscovites, some opaque minerals.
- Texture :** Phanero-crystalline where the plagioclases exhibit very distinct convolute zoning. Some zoned crystals also show albite and albite-carlsbad twinning. Myrmekitic intergrowths of plagioclases and quartz are common. There are some big microclines with tartan twinning and rare perthitic textures. The biotites occur as big euhedral to subhedral crystals and some of the biotites contain small quartz grains as inclusions. There are also some biotites which contain zircon inclusions forming distinct pleochroic haloes. The amphiboles exhibit characteristics hornblende optical characteristics with clear pleochroism. Muscovite shows clear elongation with some lamellar twinning, characteristic cleavage and high interference colours. Epidotes occur as very fine - grained aggregates. The cubic crystals of pyrites and magnetites) are concentrated within the quartz and feldspars.
- Accessory Minerals :** Sphene is the common and abundant accessory with little zircon and apatite.
- Estimated Composition :** plagioclases : 45 %, K -feldspars : 7 %, quartz : 25 %, biotites : 10 %, hornblendes : 10 %, muscovite and epidote : 1 %, opaque minerals : 2 %.
- Petrographic Name :** Biotite - Hornblende - Granodiorite.
- 3. Sample :** TG 48, collected from the contact zone between the tonalites and the diorites.

Handspecimen : Melanocratic with some white spots. Plagioclases and biotites can be easily identified.

Identified Minerals : plagioclases, quartz, some K - feldspars, biotite, hornblende, some pyroxenes and opaque minerals. There are also some unidentified deep red minerals .

Texture : Phanerocrystalline; the plagioclases are zoned and exhibit albite twinning. Some plagioclases contain very fine - grained secondary micas at their cores, and there are many sieve - textured plagioclase crystals. Microclines show both tartan and simple albite twinning. The quartz grains exhibit embayement textures at their contacts with plagioclases. The biotites and hornblendes occur as aggregates and rarely as perfect euhedral crystals scattered within the plagioclase feldspars.

Accessory Minerals : Apatite and sphene are the common accessories with some zircon.

Estimated Composition : plagioclases : 70 %, K - feldspars : 5 %, quartz : 10 %, biotite : 7 %, hornblende : 5 %, pyroxenes : 1 %, opaque Minerals : 2 %.

Petrographic Name : Tonalite.

4. Sample : TG 49, collected from the centre of the diorite body.

Handspecimen : Melanocratic, fine - grained.

Identified Minerals : plagioclase, pyroxene, biotite, hornblende, opaque minerals and very little quartz.

Texture : Hollocrystalline, fine - grained, with subhedral and rare euhedral crystals. The plagioclases exhibit albite and occasionally albite-carlsbad twinning; some plagioclases exhibit slight zoning and contain fine -grained secondary micas at their cores. Pyroxene is commonly represented by augite crystals which show second order green - blue interference colours. Hornblende occur as fine - grained aggregates associated with the pyroxenes. Biotite commonly occurs as subhedral crystals. There are some biotite crystals containing zircon crystals with haloes at their boundaries. The opaque minerals are

scattered all over and they exhibit very distinct skeletal and graphic textures, forming series of elongated ribbons. Others occur scattered within the plagioclases. Some of the opaque minerals show deep red shading at their boundaries especially under crossed polars. Very rare crystals are fully deep red both under parallel and crossed polars.

Accessory Minerals : Some sphenes and very rare zircon crystals.

Estimated composition : Plagioclase : 30 %, aegerine - augite : 25 %, biotite : 20 %, hornblende : 10 %, opaque minerals : 12 %, quartz : 5 %.

Petrographic Name : (Pyroxene) Diorite.

5. Sample : TG 52, Collected from the contact zone between the diorites and the tonalites.

Handspecimen : Porphyritic with discernible hornblende and biotite phenocrysts.

Identified Minerals : plagioclase, biotite, hornblende, pyroxene (augite), some quartz and opaque minerals.

Texture : Porphyritic with large subhedral phenocrysts of biotites and hornblende. Plagioclase exhibits albite twinning. Biotite encloses many quartz and opaque minerals. Some biotites exhibit twinning. The groundmass is constituted by aggregated biotite, hornblende and pyroxene, which show reaction relationships at their boundaries. The pyroxenes are commonly elongated and exhibit clear lamellar twinning, while others show embayment textures. The opaque minerals occur as scattered euhedral to subhedral crystals.

Accessory Minerals : Zircon is the only common accessory.

Estimated Composition : plagioclase : 40 %, biotite : 20 %, hornblende : 20 %, pyroxene : 10%, quartz : 5 %, opaque minerals : 5 %.

Petrographic Name : **Biotite - Hornblende - Quartz Diorite.**

6. Sample : TG 53, Collected from a dike that cuts the diorites

Handspecimen : Leucocratic, very fine - grained rock from an aplite dike.

Identified Minerals : quartz, K - feldspars, muscovite, some biotite and hornblende, little plagioclase.

Texture : Aphanitic; quartz and feldspars commonly show intimate micrographic intergrowths. Feldspars are commonly twinned, muscovites show characteristic basal cleavage and high interference colours. Hornblende occurs as elongated laths while biotites are equigranular subhedral to euhedral. There are some plagioclases which show lamellar textures.

Accessory Minerals : Zircon.

Estimated Composition : K - feldspars : 40 %, quartz : 35 %, muscovite : 40 %, plagioclases : 5 %, biotite : 7 %, hornblende : 5 %.

Petrographic Name : **Micro - Granite.**

7. Sample : **TG 99**, Collected from a dike that cuts the wall rocks near the eastern contact of the pluton.

Handspecimen : Leucocratic, porphyritic rock that contains many visible plagioclase and quartz grains set in fine - grained white material. The dike is affected by a swarm of quartz veins and it shows some lineation at its contact with the country rocks.

Identified Minerals : quartz, plagioclases, K - feldspars, muscovite, some biotite and rare opaque minerals.

Texture : Porphyritic with coarse plagioclase and quartz crystals set in very fine - grained muscovite rich matrix. K - feldspars occur as fine - grained aggregates and rarely as big crystals enclosing very fine - grained aggregates of muscovites, giving them sieve (mottled) appearances. Biotites are scattered as fine anhedral crystals while the opaque minerals are commonly fine - grained and concentrate in ribbons, except for some perfect cubic crystals of pyrite scattered through the rock.

Accessory Minerals : Rare zircon.

Estimated Composition : quartz : 10 %, muscovite : 35 %, K -feldspar : 20 %, plagioclases : 25 %, biotite : 5 %, opaque minerals : 5 %.

Petrographic Name : **Micro - granite**

8. Sample : **TG 112**, Collected from an aplite dike cutting metamorphic rocks on the western side of the pluton.

Handspecimen : Leucocratic, fine - grained with sugary texture.

Identified Minerals : quartz, K - feldspar, some biotite and rare muscovite, opaque minerals and secondary calcite.

Texture : Quartz and K - feldspar form some coarse crystals but commonly occur as fine - grained aggregates with micrographic intergrowths. Feldspars exhibit Carlsbad twinning. Biotites occur as anhedral to subhedral grains while muscovite is very fine - grained and is enclosed as a secondary product within coarse feldspar crystals. The opaque minerals are perfect cubic crystals (pyrites).

Accessory Minerals : Rare zircon.

Estimated Composition : quartz : 45 %, K - feldspars 45 %, biotite : 5 %, muscovite : 3 %, opaque minerals : 2 %.

Petrographic Name : **Micro - Granite.**

B. 2. METAMORPHIC ROCKS

9. Sample : **TG 95**, Collected far away from the pluton (about 3 km from Negash along the Wukro - Negash main road).

Identified Minerals : quartz, plagioclase, K - feldspars, Sericite.

Texture : The rock exhibits relict porphyritic texture with quartz and plagioclase phenocrysts. Plagioclases are commonly twinned according to the albite law. Some of the quartz grains are strained along the foliation direction. The matrix is made of sericites, quartz and alkali feldspars which form elongated fine aggregates. There are some black fine grained aggregates of minerals which are dark at

parallel polars and are elongated at some angle to the general foliation; they may represent glass shards of original fiammes within ignimbritic rocks that have survived metamorphism.

Accessory Minerals : Some tourmalines which are elongated almost perpendicular to the foliation direction. There are also some zircon.

Parent Material : The mineral assemblage and texture indicate a volcanic pyroclastic rock as parent material.

10. Sample : TG 120, Wall rock collected from the Western contact of the pluton.

Identified Minerals : plagioclase, quartz, K - feldspars, muscovite, epidote, some biotite, opaque minerals, allanite.

Texture : The rock exhibits relict porphyritic texture with coarse plagioclases, quartz and K - feldspar phenocrysts. The plagioclase exhibits albite twinning while the K - feldspars typically show polysynthetic twinning. The phenocrysts are set in fine, equigranular matrix composed of muscovite, some epidotes and K - feldspars. The minerals do not exhibit strong foliation and no phenocryst is strained. There a lot of red minerals which exhibit zoned and corona textures with distorted shapes, they may represent metamictic allanite whose lattice has been destorted by radioactive elements such as Th and U. The opaque minerals are commonly represented by pyrites which form perfect cubic crystals. The mineralization is clearly post metamorphic because the opaque minerals contain some quartz and feldspars and are superimposed over metamorphic textures..

Accessory Minerals : Abundant zircon.

Parent Material : The dominance of quartz, muscovite and K - feldspars may indicate an original acid volcanic rock. But the presence of epidotes and zircons show that the protolith had high Ca contents and contained abundant zircon. This points to a sedimentary protolith.

- 11. Sample :** **TG 125**, Wall rock collected from the Western contact of the pluton, close to the contact.
- Identified Minerals :** quartz, feldspars, epidote, garnet, muscovite, chlorite, some biotite, opaque minerals.
- Texture :** The rock exhibits relict porphyritic texture with quartz and plagioclase phenocrysts. Plagioclases exhibit zoning and albite twinning. Epidotes, chlorites, sericite, and biotites show some intergrowths and constitute the matrix. Garnet forms coarse grained crystals which are fractured at their margins and enclose many quartz grains. Skeletal garnets are also observed. There are a lot of opaque minerals with perfect cubic habits (pyrites) scattered all over the rock.
- Accessory Minerals :** A lot of fine zircon, sphene and apatite.
- Parent Material :** The presence of quartz and plagioclase porphyroclasts and chlorites - epidote - sericite matrix favours a porphyritic basic volcanic rock as parent material. The garnets may indicate a thermal metamorphic effect of a slightly higher grade (Upper green schist facies).
- 12. Sample :** **TG 47**, A roof rock collected from one of the roof pendants within the intrusion.
- Identified Minerals :** quartz, feldspars (dominantly plagioclases), epidote, chlorite and opaque minerals.
- Texture :** The rock is constituted by very fine - grained, elongated (lath - shaped) epidotes and chlorites set in a finer grained quartz and granoblastic feldspar-rich matrix. There is no trace of foliation in the rock and the epidotes and chlorites which show some recrystallization are oriented randomly. There are some fine - grained opaque minerals scattered all over the other minerals.
- Accessory Minerals :** zircon.
- Parent Material :** The mineral assemblage and the texture indicates a basaltic parent material affected by lower grade dynamothermal and thermal metamorphism.

- 13. Sample :** TG 82, Collected far away from the pluton
- Minerals Identified :** quartz, microcline, plagioclase, muscovite, sericite, epidote, chlorite, calcite crystals.
- Texture :** Coarse quartz crystals which are strongly strained and fragmented, microclines, and rare muscovite crystals occur as larger crystals set in a fine grained aggregate of quartz, some plagioclases, sericite, epidotes and chlorite. Some of the coarse muscovites are surrounded by fine - grained sericites which intergrow with the chlorites and epidotes. Calcite occurs as patches within the matrix.
- Parent Material :** The dominance of deformed and strained quartz, microclines and muscovites with little plagioclases and mafic minerals, together with the presence of abundant calcite indicates a calcite rich sandstone as a protolith.
- 14. Sample :** TG 118, Collected from the western area away from the pluton. In handspecimen, the rock contains some fragmented quartz inclusions and is cut by quartz veinlets.
- Identified Minerals :** quartz, epidote, sericite, chlorite, rare feldspars, opaque minerals, allanite, and rare calcite.
- Texture :** There are some coarse quartz grains (relict phenocrysts) set in an aggregate of very fine - grained quartz, epidotes, sericite, and rare feldspars which are fine and can only be identified at higher magnifications. The fine - grained minerals (except quartz) are oriented and elongated. Some of the coarse quartz grains are strained along the general foliation direction. There are rare muscovite crystals which are fragmented at their margins and surrounded by fine - grained sericite. The rock is cut by quartz veinlets which are composed of equigranular, quartz grains. The veinlets which are generally oriented at some angle to the foliation of the rock occasionally exhibit sinuous features, and contain some chlorites. There are red minerals

(metamictic allanites) which occur both in the matrix and within the quartz veinlets enclosing the quartz grains. There are some opaque minerals scattered all over the minerals.

Accessory Minerals : Abundant zircon and apatite

Parent Material : A clay rich sandstone with calcite cement affected by very low grade metamorphism.

15. Sample : TG 63, Collected about sixty meters away from the eastern contact.

Identified Minerals : quartz, sericite, muscovite, rare feldspars, opaque minerals.

Texture : There are very rare coarse quartz crystals set in very fine - grained aggregate of quartz, sericite and few feldspars, which shows clear orientation with the sericites elongated along the foliation. The larger quartz crystals are sometimes fragmented. There are some muscovites which are coarser and oriented at an angle to the general foliation trend. There are several opaque minerals which do not show preferred orientation indicating that they were formed after regional metamorphism.

Accessory Minerals : Abundant zircon.

Parent Material : The mineral assemblage and the prevailing metamorphic textures favour basic porphyritic igneous rock as a protolith.

16. Sample : TG 71, Wall rock collected from the South eastern contact

Identified Minerals : garnet, epidote, plagioclase, microcline, rare muscovite, chlorite and quartz, opaque minerals.

Texture : The garnets are coarse -grained exhibiting dendritic crystal growths, enclosing many plagioclases. Epidotes, some sericites and chlorites show intimate intergrowths with fine grained equigranular aggregates of quartz and K - feldspars. This exhibits tartan twinning typical of microcline. The matrix shows some recrystallization and foliation. There are rare opaque minerals.

Accessory Minerals : Rare zircon.

Parent Material : The presence of dominant garnets, plagioclases and epidotes with little quartz, K-feldspars and muscovites indicates an intermediate volcanics.

17. Sample : TG 79, Collected far away from the pluton.

Identified Minerals : quartz, muscovite and sericite, chlorite, little K - feldspars, calcite and opaque minerals.

Texture : The rock is highly foliated, composed of fine - grained aggregates of muscovite and sericite which are elongated along the foliation, in which coarser quartz and chlorites are enclosed. The coarser grains of chlorites exhibit fragmentation along their longer axes while quartz large crystals are strained along the foliation direction. There are many calcite bands totally enclosed by elongated chlorites. There are many fine - grained opaque minerals distributed along the foliation. The opaque minerals also show some fragmentation along the foliation, which suggests a non post -metamorphic origin.

Parent Material : The mineral assemblage and the texture of the rock indicate pelitic sedimentary rock (clay rich sandstone cemented by calcite) which was affected by cataclastic metamorphism.

18. Sample : TG 87, Collected at the southern part of the pluton from the wall rocks. The rock is cut by a complicated net work of quartz veins and veinlets.

Identified Minerals : quartz, sericite, little chlorite, rare feldspars, pyrite.

Texture : A fine - grained aggregate of sericite, quartz, some chlorite and feldspars contains a few large quartz crystals which show fragmentation at their margins. There is a quartz veinlet composed of equigranular quartz crystals, hosted by very fine - grained aggregates of sericites, some chlorite, quartz and rare feldspars. The quartz grains forming the veinlets are stained by brownish minerals and there are some opaque minerals with perfect cubic habits (pyrites).

Parent Material : The dominance of sericites and quartz and the texture may indicate an acidic volcanics as a parent rock.

19. Sample : TG 60, Collected at the eastern contact.

Identified Minerals : epidotes, sericite, quartz, some chlorite, some feldspars, rare biotite, some opaque minerals.

Texture : The rock is foliated with very fine - grained aggregates of epidotes and quartz, some sericite and chlorites. There are some larger muscovite grains which are highly fragmented. These muscovite grains are elongated along the foliation. There are also rare muscovite crystals transformed to the sericites which are oriented perpendicular to the foliation. There are many brownish - red stains along the foliation.

Accessory Minerals : Rare zircon and apatite.

Parent Material : The relict porphyritic textures and the dominance of muscovites and quartz indicate a acidic volcanic rocks as parent material.

20. Sample : TG 115, Wall rock collected from the western area (Adi Desta region) close to the contact.

Identified Minerals : quartz, feldspars, muscovite, sericite, biotite, chlorite, opaque minerals.

Texture : There are quartz grains with nodular textures and many coarse muscovite which are highly fragmented and extensively transformed into fine - grained sericite. These larger mica crystals are set in very fine - grained, highly foliated aggregates of sericites and quartz. The foliation direction shows some deflection by the around larger mica crystals, which themselves are strained, aligned, and fragmented along the foliation direction. There are many muscovite, chlorite and rare biotite fragments which are aligned at some angle from the foliation direction. Some of these muscovites show poikilitic textures. The minerals are generally enclosed by equigranular quartz aggregates

indicating late silicification. There are some opaque minerals scattered in the rock.


Accessory Minerals : Rare zircon and apatite.

Parent Material : The dominance of muscovites and quartz together with textural evidence indicates an acidic igneous rock as parent material..

DECLARATION

I, the undersigned, declare that this thesis is my work and that all sources of material used for the thesis have been dully acknowledged.

ASFAWOSSEN ASRAT



Asfawossen A.

SCHOOL OF GRADUATE STUDIES

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